PIERRE AUGER OBSERVATORY

Surprising results on the composition of the highest energy cosmic rays

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Fermilab

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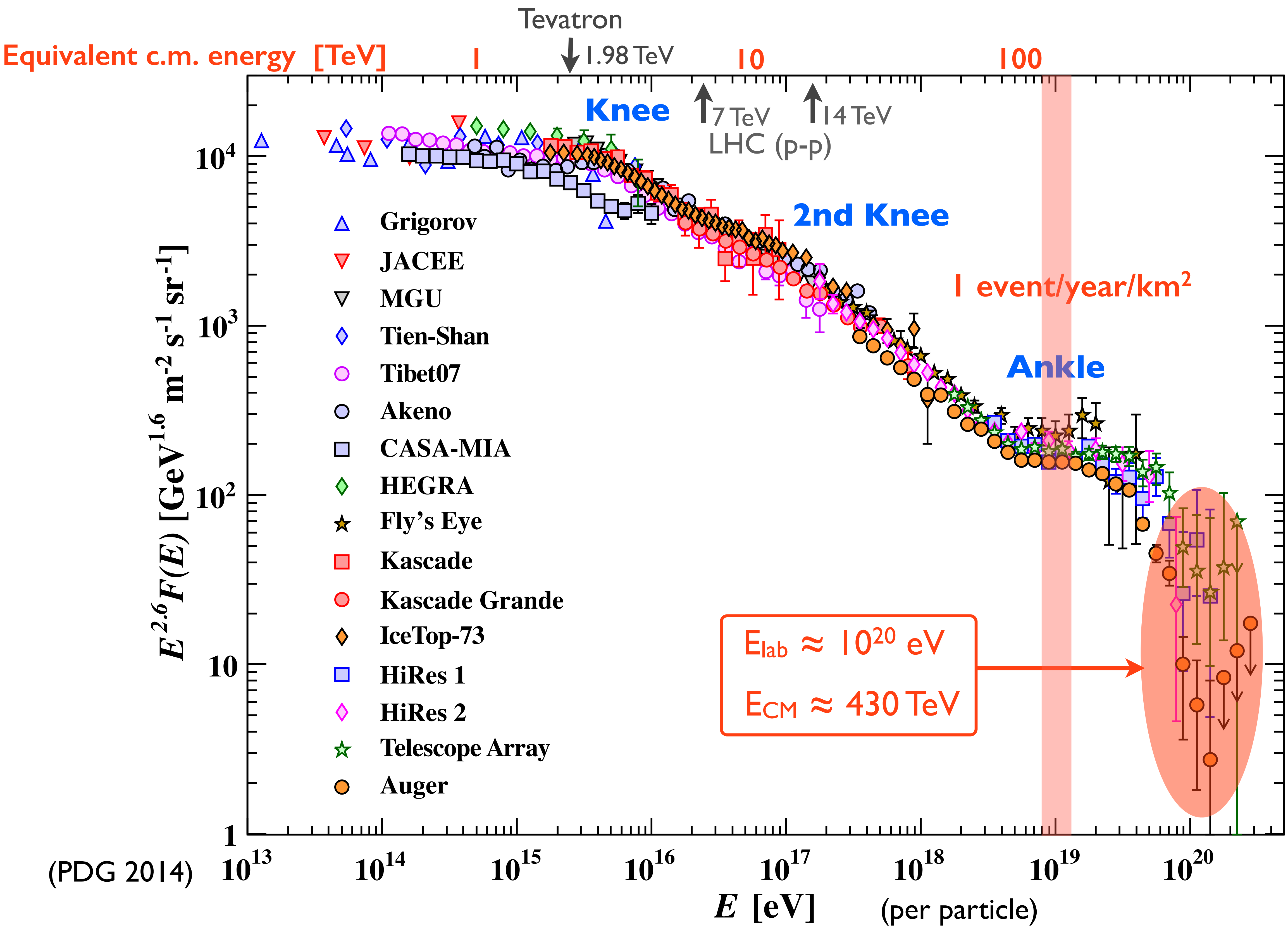
Ultra High Energy Cosmic Rays

➡ low-luminosity high-energy fixed target experiment



$$E_{lab} = 10^{20}\ \text{eV}$$

$$E_{CM} = 430\ \text{TeV}$$

With present accelerator technology:

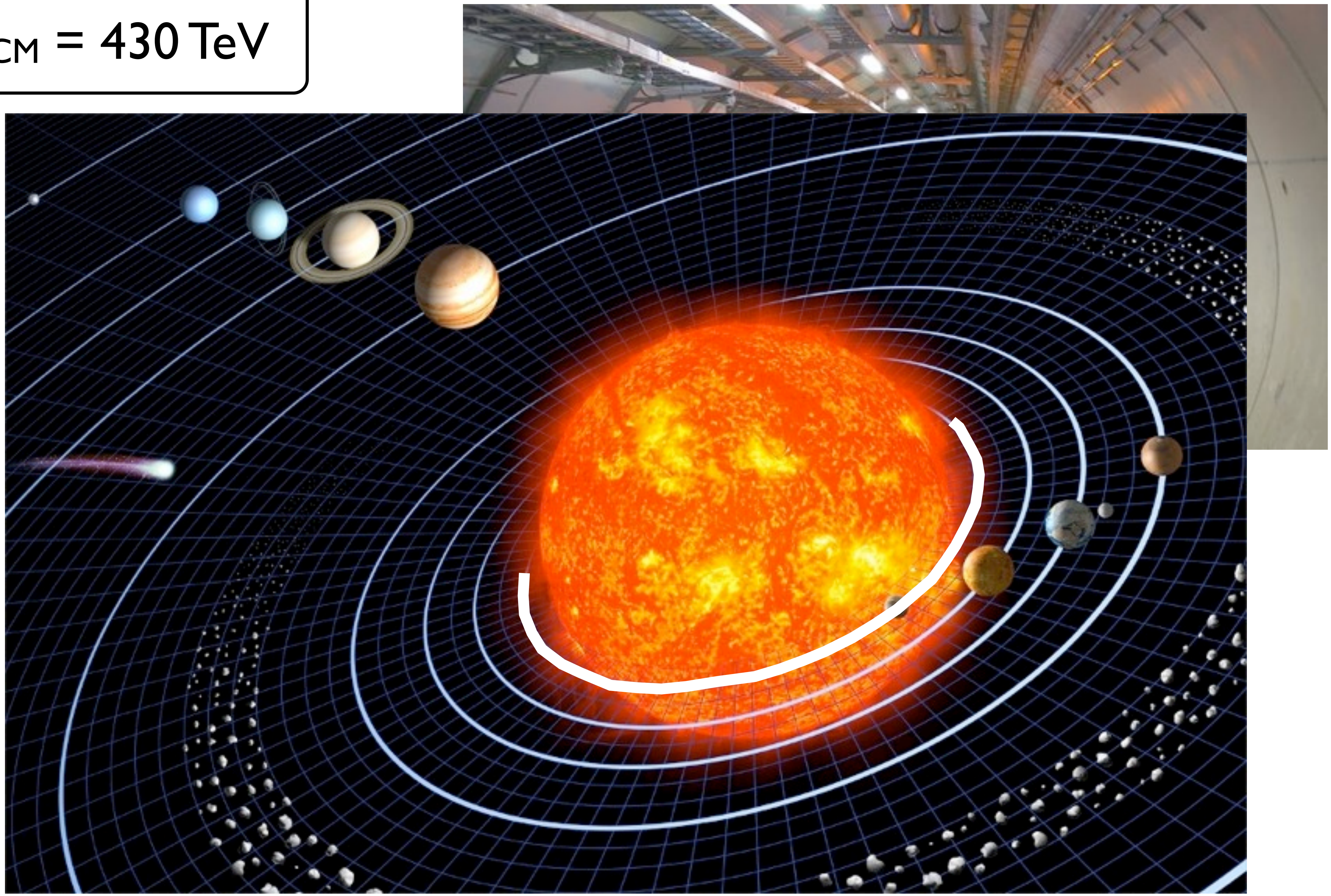
LHC: 27 km circumference, E_{CM} = 14 TeV

$E_{lab} = 10^{20}$ eV

$E_{CM} = 430$ TeV

With present accelerator technology:

LHC: 27 km circumference, $E_{CM} = 14$ TeV



Orbit of Mercury (3.6×10^8 km), LHC acceleration time of 815 years

Ultra High Energy Cosmic Rays

What are they?

Where are they coming from?

How do they **interact?**

Where are they coming from?

Sources of UHECR

Traditionally:

1. Top-down

massive (high energy) object decays or interacts → produces lesser energy particles (UHECRs)

monopoles; topological defects; superheavy relics; UHECRONs; z-bursts; etc

(Schramm & Hill 1983; Hill 1983; Weiler 1982; Bhattacharjee & Sigl 1995; Berezinsky et al. 1997; Kolb et al. 1998; Chung et al. 1998; Albuquerque et al 1999; etc.)

2. Bottom-up

"ordinary" energy particle gets accelerated up by astrophysical means to higher energies

AGN hot spot, jets, central BH; cluster shocks; colliding galaxies; gamma ray bursts; neutron stars; etc.

(Hillas 1984; Thorne et al. 1986; Biermann & Strittmatter 1987; Vietri 1995; Waxman 1995; Kang et al 1996; Olinto et al. 1999; etc.)

Where are they coming from?

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~~(Schramm & Hill 1983; Hill 1983; Weiler 1982; Bhattacharjee & Sigl 1995; Berezinsky et al 1997; Kolb et al. 1998; Chung et al. 1998; Albuquerque et al 1999; etc.)~~

disfavored by photon & neutrino limits

(Pierre Auger Collaboration 2008, 2011, 2013)

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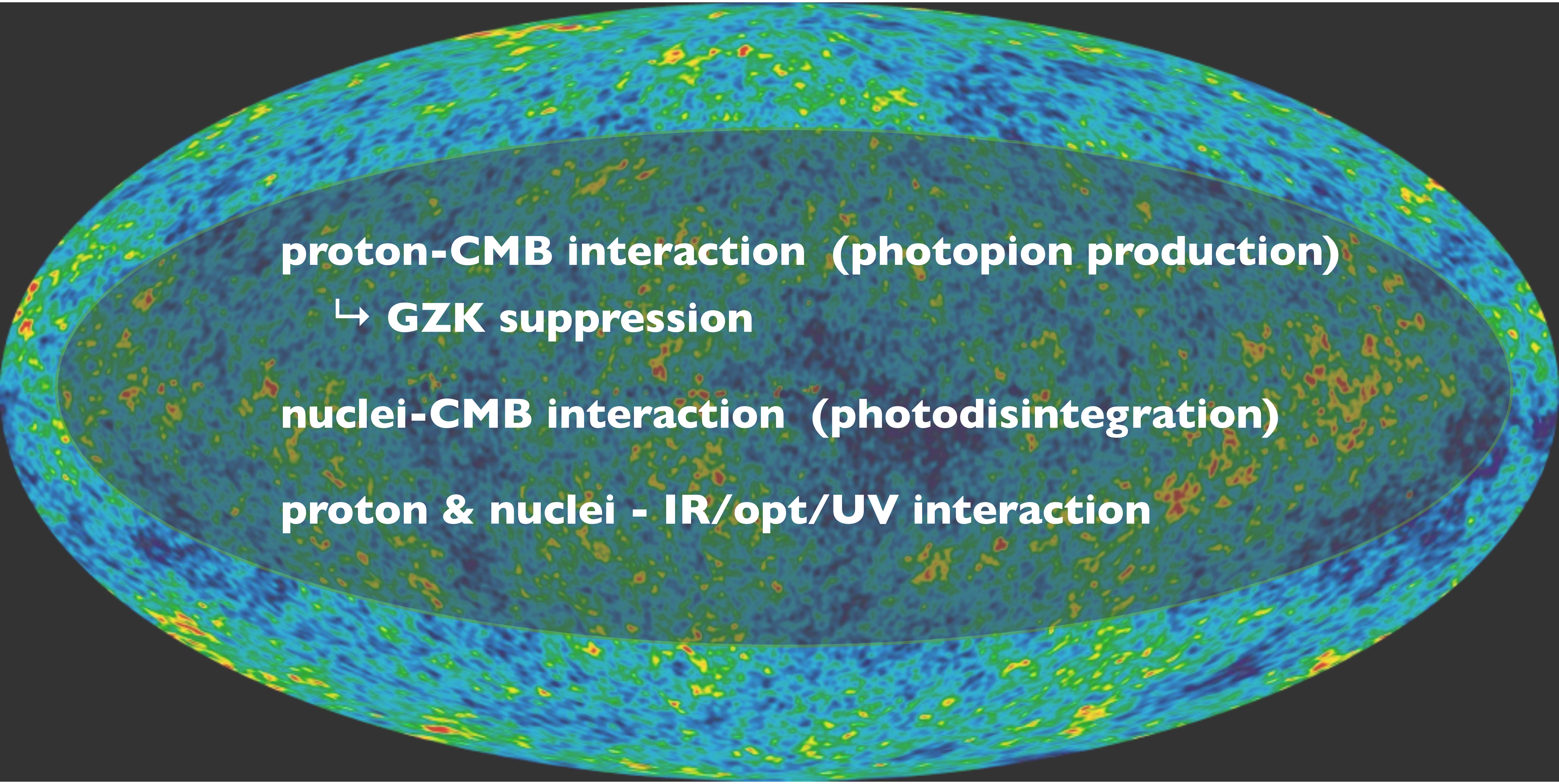
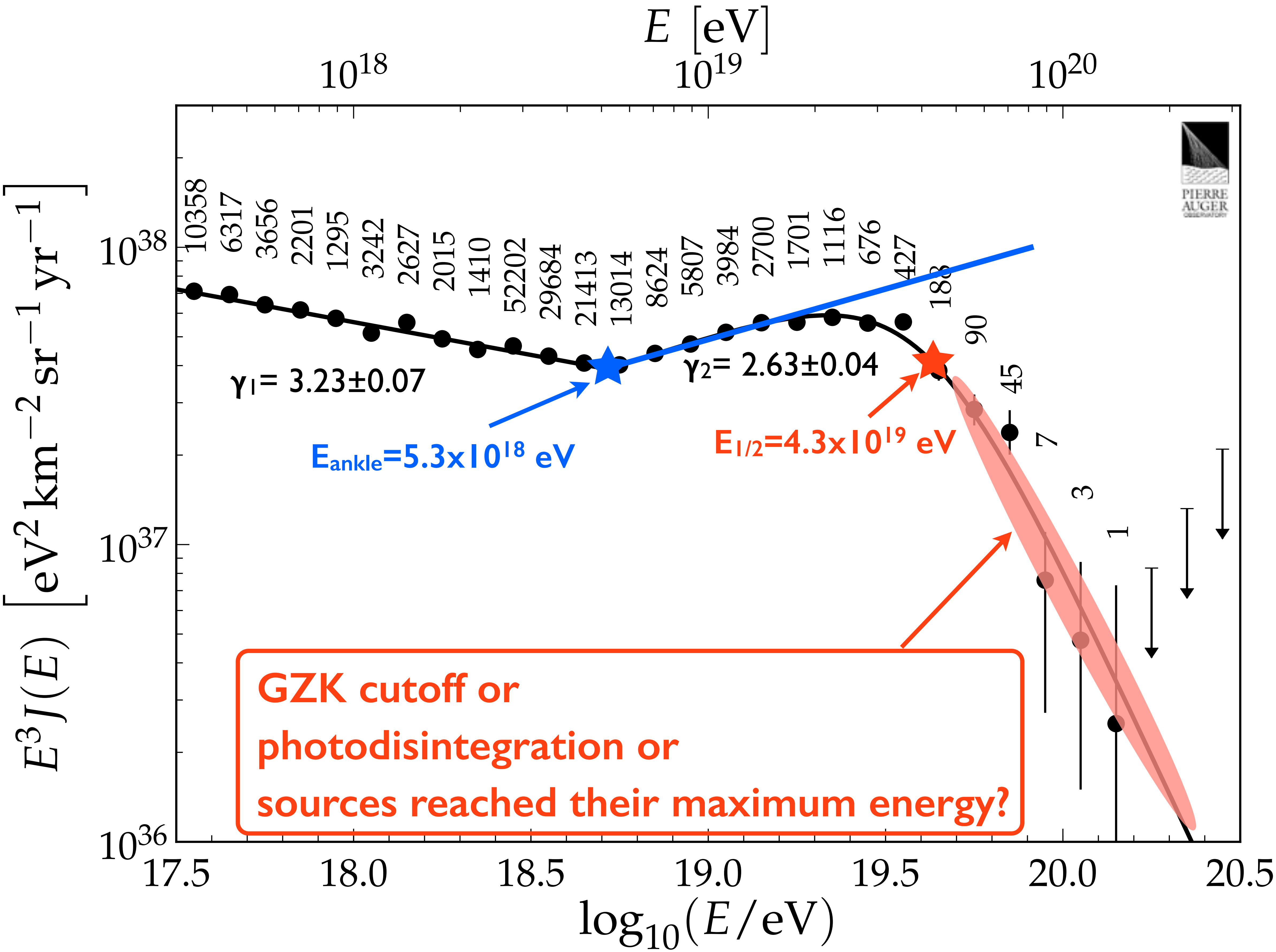
UHECRs ≳ 5×10^{19} eV need to come from nearby



→ flux suppression

Energy spectrum - suppression observed at high energy



UHECR candidates

- **Photons, neutrinos:** still possible but very low flux
- **Protons**: abundant throughout the universe - many astrophysical locations
  effectively stable - lose energy during propagation,
  neutron decays back into proton
- **Heavier nuclei:** less abundant
  able to accelerate to a higher energy in a given source

Diffuse shock acceleration

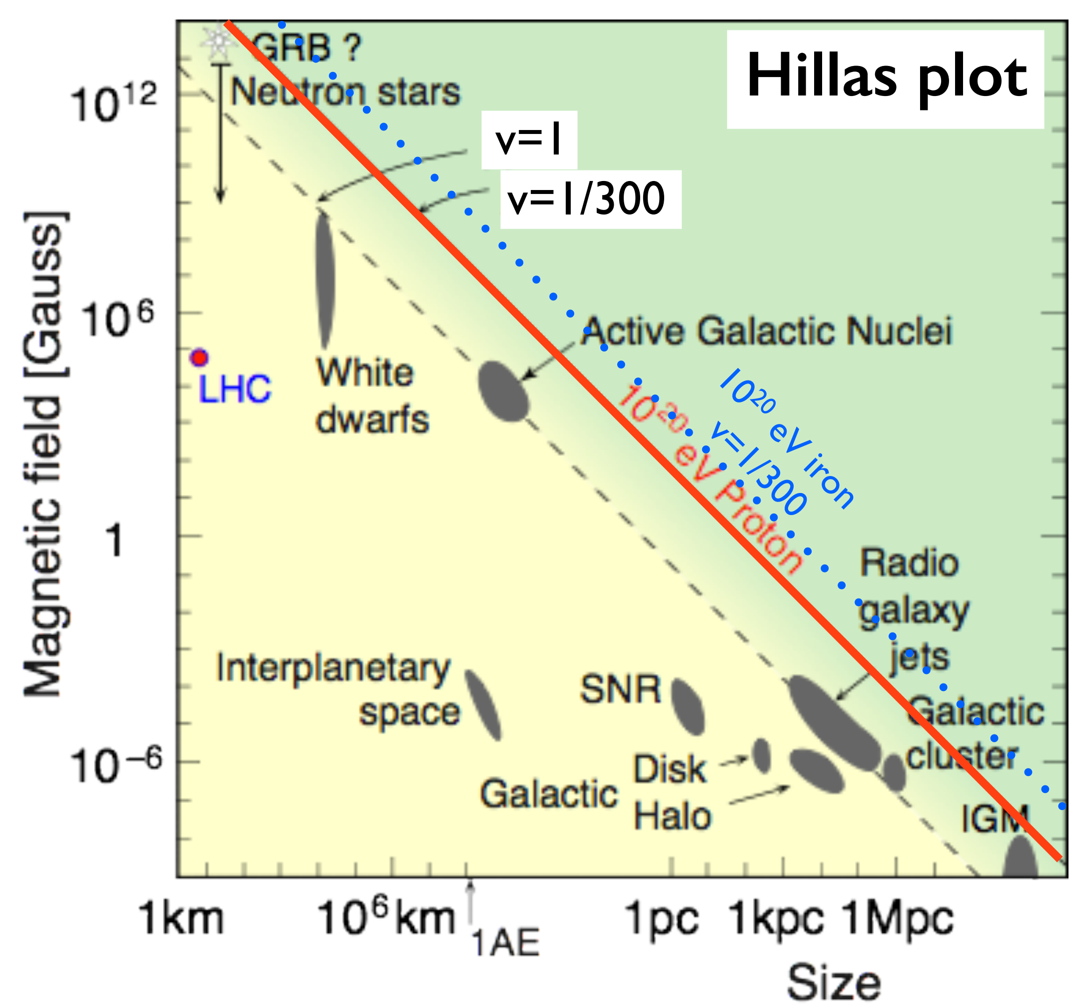
$$\boxed{E_{\rm max} \approx Z\, v \left(\frac{R}{\rm kpc}\right)\left(\frac{B}{\mu G}\right) \times 10^{18}{\rm eV}}$$

charge

shock velocity

acceleration region

magnetic field



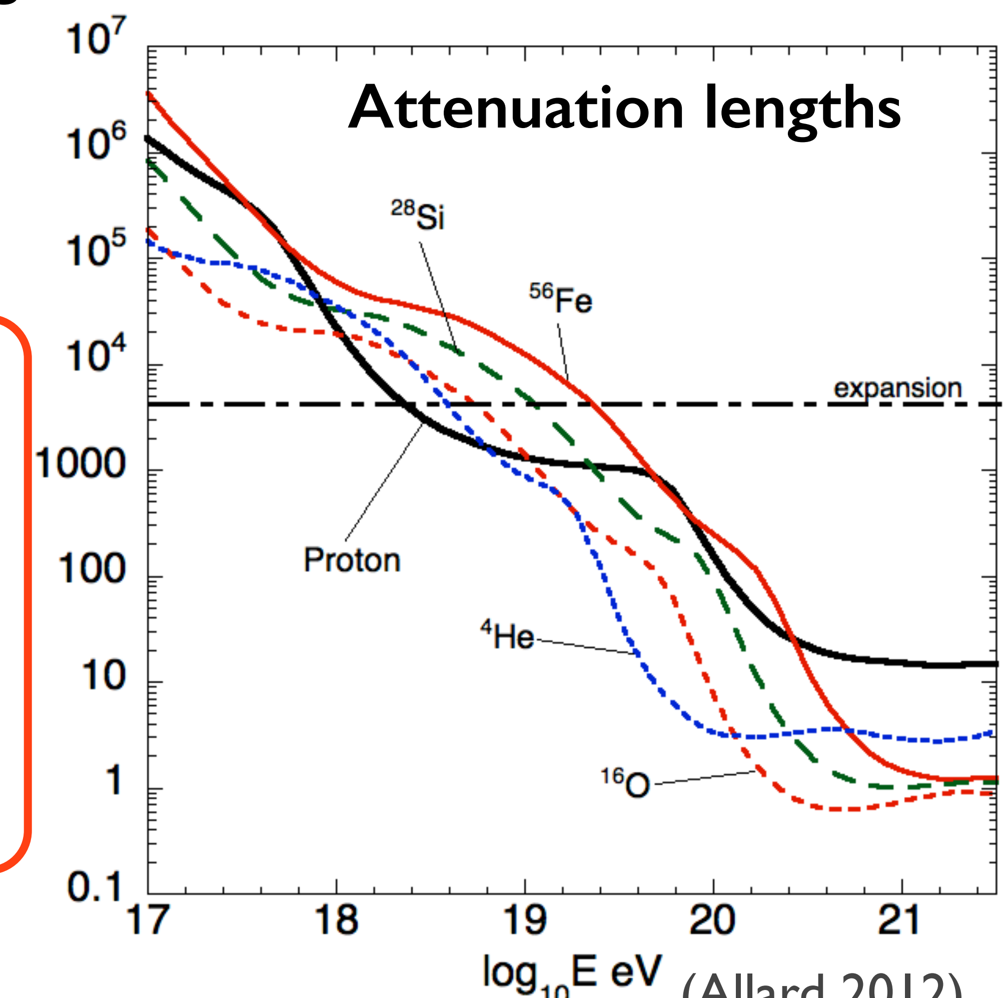
UHECR candidates

- **Photons, neutrinos:** still possible but very low flux
- **Protons**: abundant throughout the universe - many astrophysical locations
  effectively stable - lose energy during propagation,
  neutron decays back into proton
- **Heavier nuclei:** less abundant
  able to accelerate to a higher energy in a given source
  lose energy, disintegrate during propagation
  Fe nucleus - most stable
  intermediate nuclei - less stable

➡ Protons are favorite

➡ Fe nuclei are most likely for heavier particles

➡ Intermediate nuclei type will vary - dependent on propagation modeling

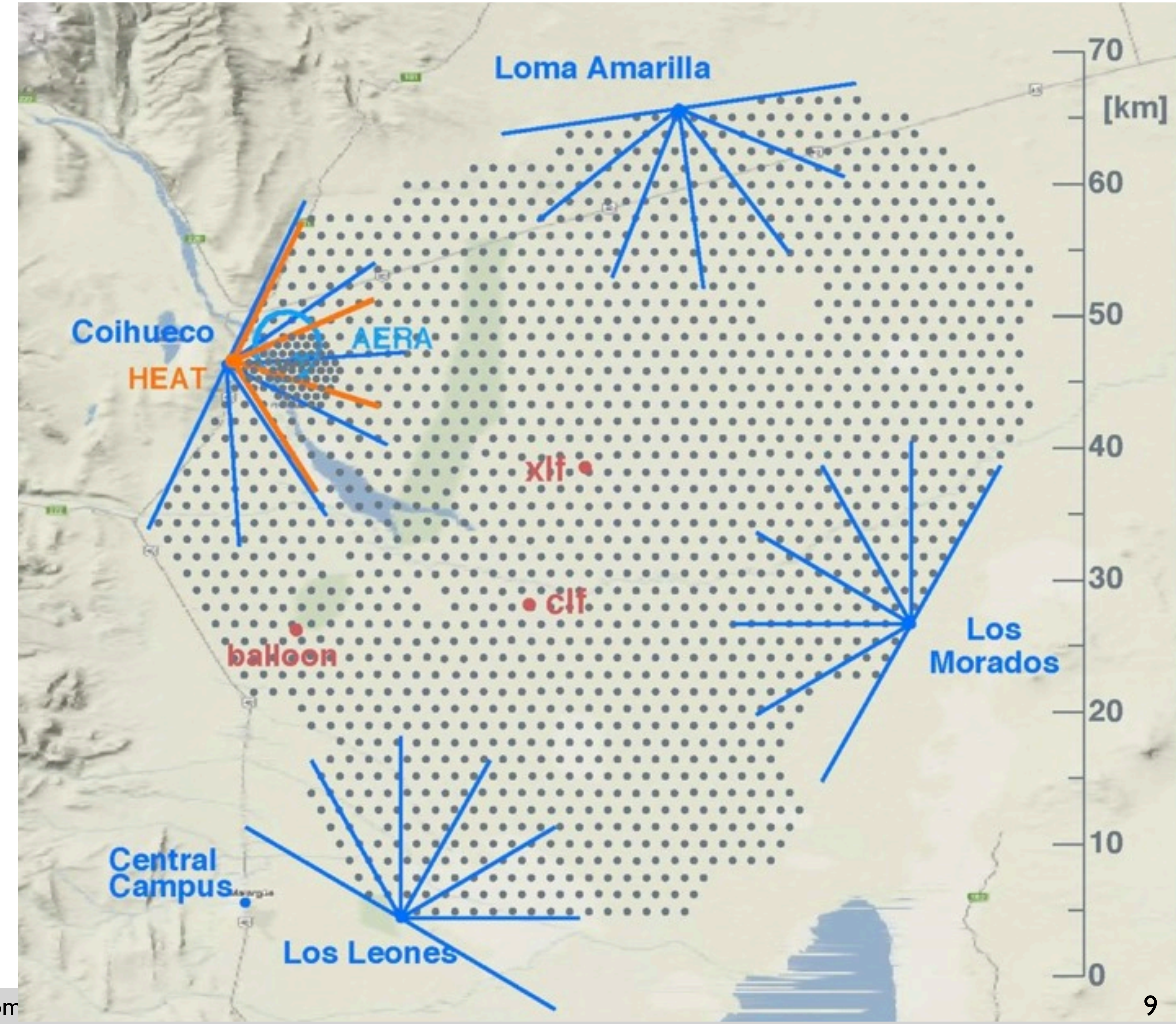


(Allard 2012)

Pierre Auger Observatory

Observe, understand, characterize the ultra high energy cosmic rays and probe particle interactions at the highest energies

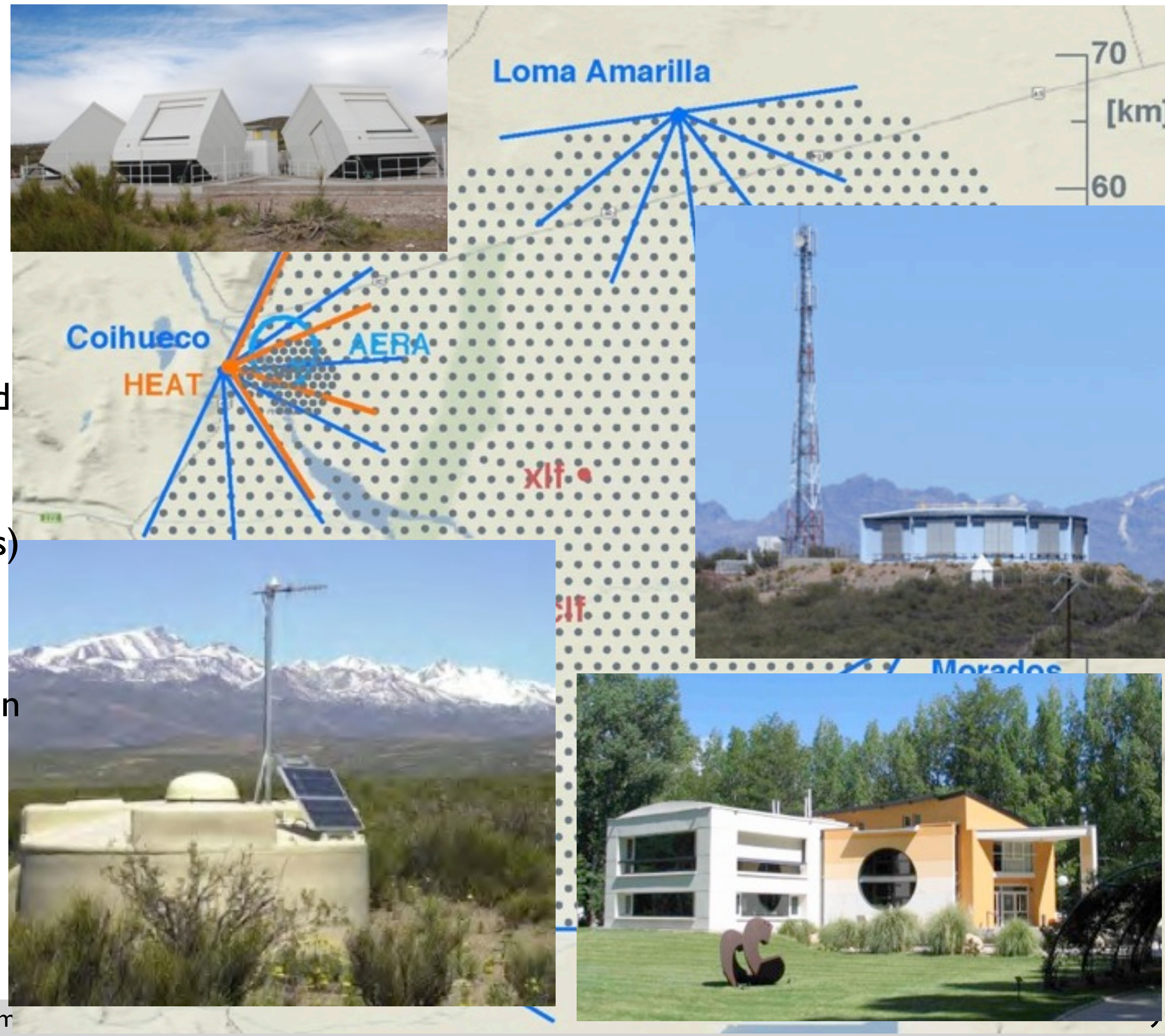
- Malargüe, Argentina
  $\sim$ 3000 km^2



Pierre Auger Observatory

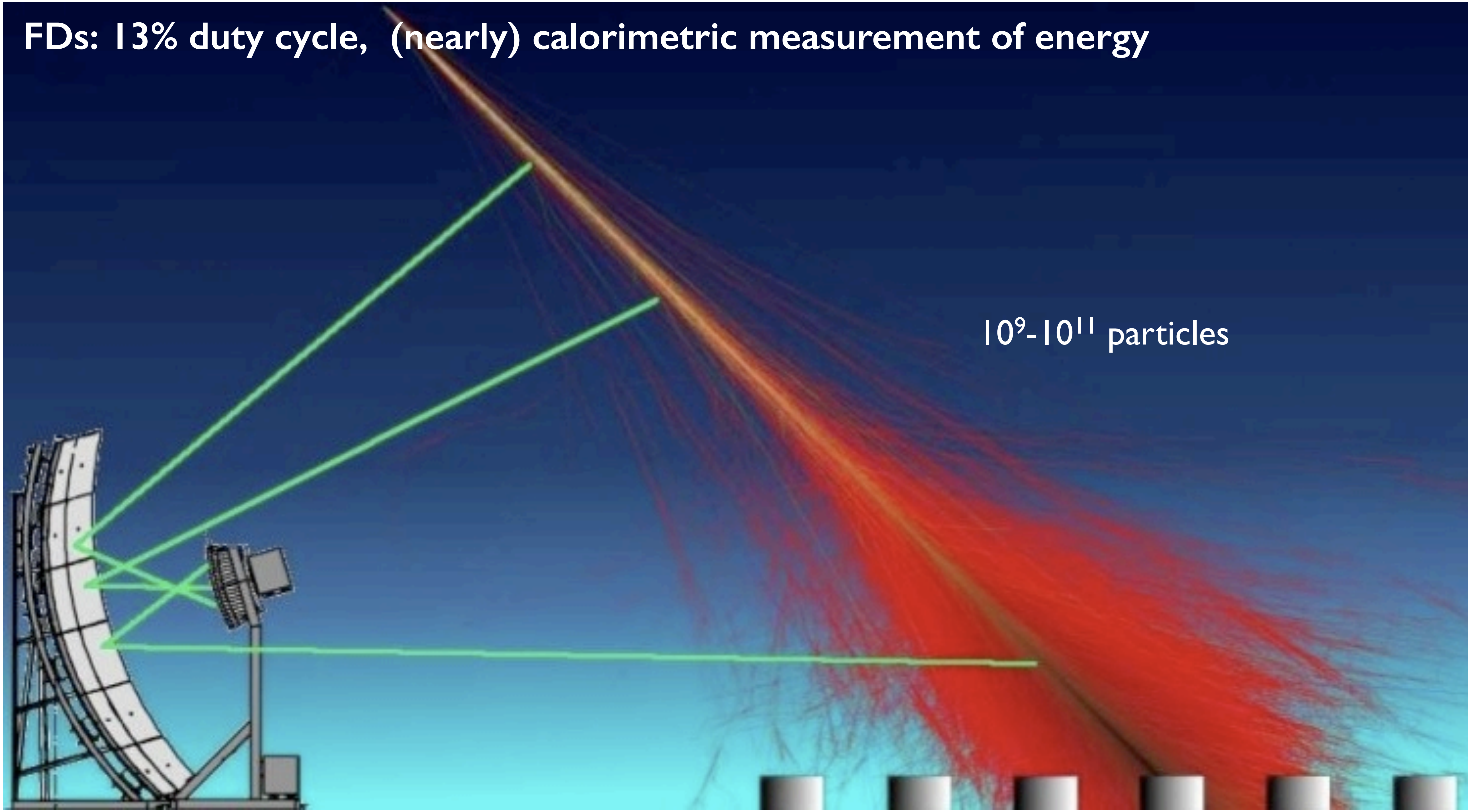
Observe, understand, characterize the ultra high energy cosmic rays and probe particle interactions at the highest energies

- Malargüe, Argentina
  $\sim$ 3000 km^2
- Surface detectors (SDs)
  - 1660 water Cherenkov detectors (WCDs) (12 tonnes, 1.5 km spacing)
  - enhancements: closer-spaced infill, muon detectors
- Fluorescence detectors (FDs)
  - 24+3 air fluorescence telescopes in periphery
  - enhancement: High Elevation Auger Telescope
- Energy range
  - main array: >10^{18} eV
  - enhancements: >10^{17} eV



Pierre Auger Observatory

Hybrid design: thoroughly understand capabilities & systematic uncertainties of both detectors



SDs: 100% duty cycle, measure particle density

Pierre Auger Observatory

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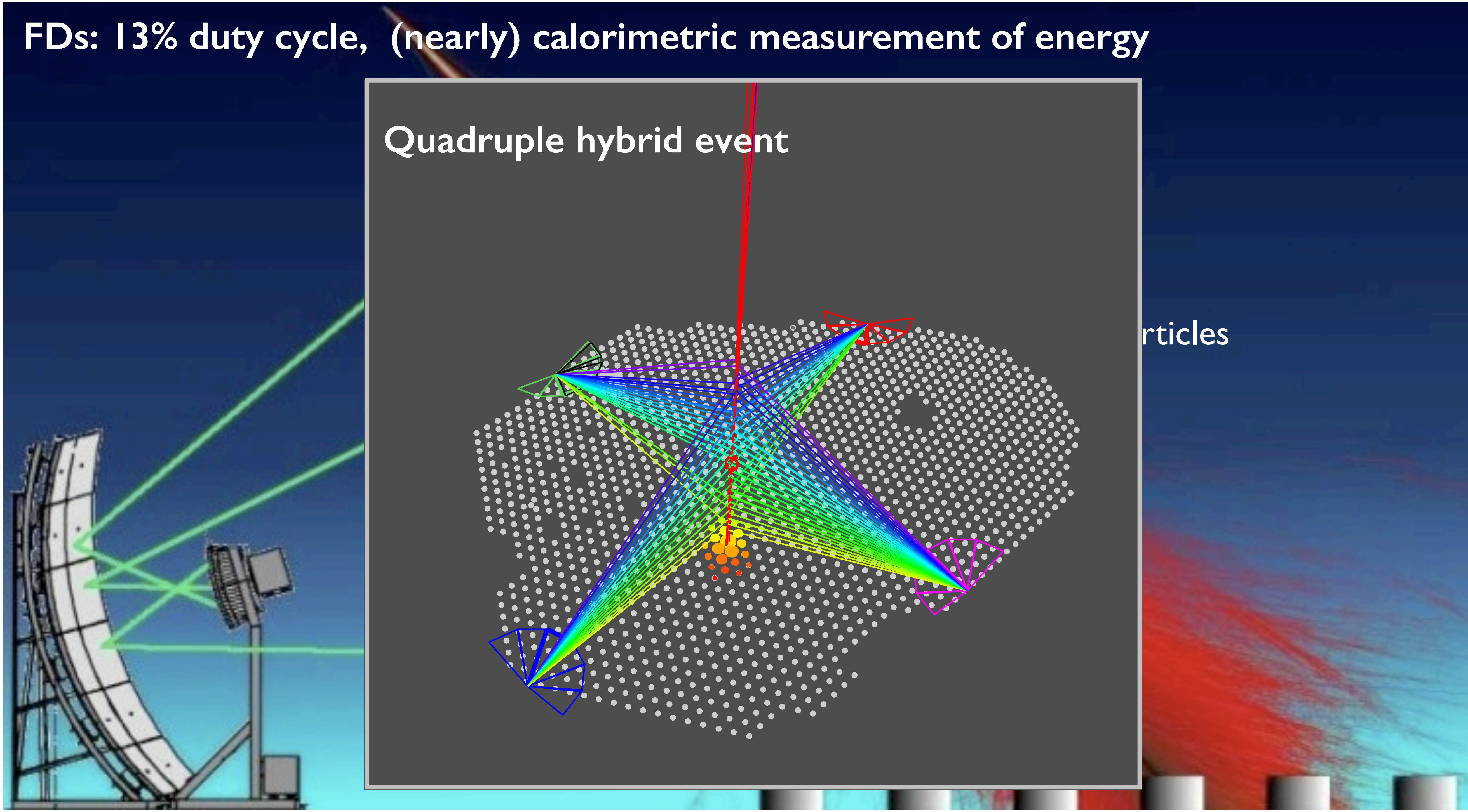
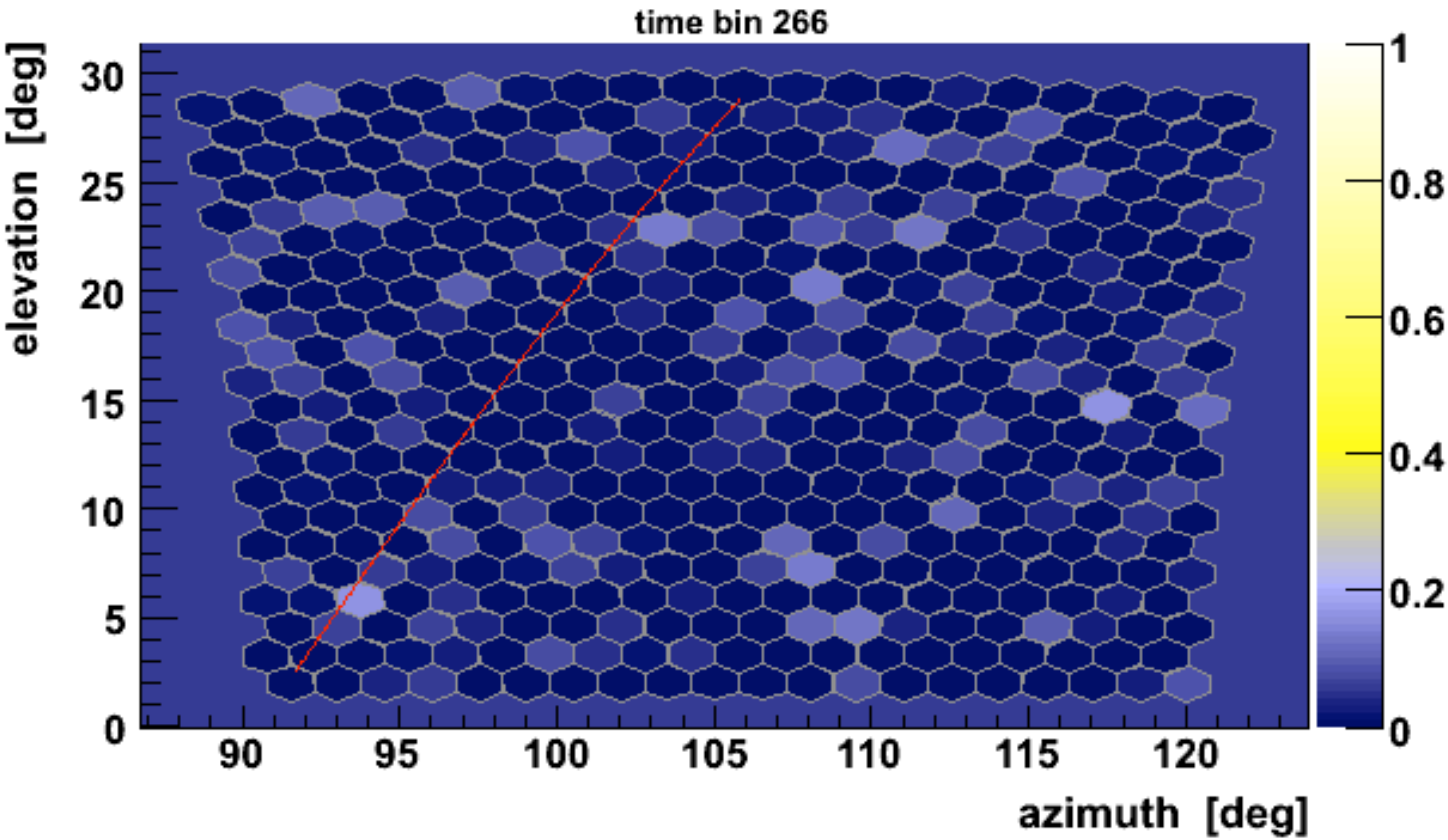


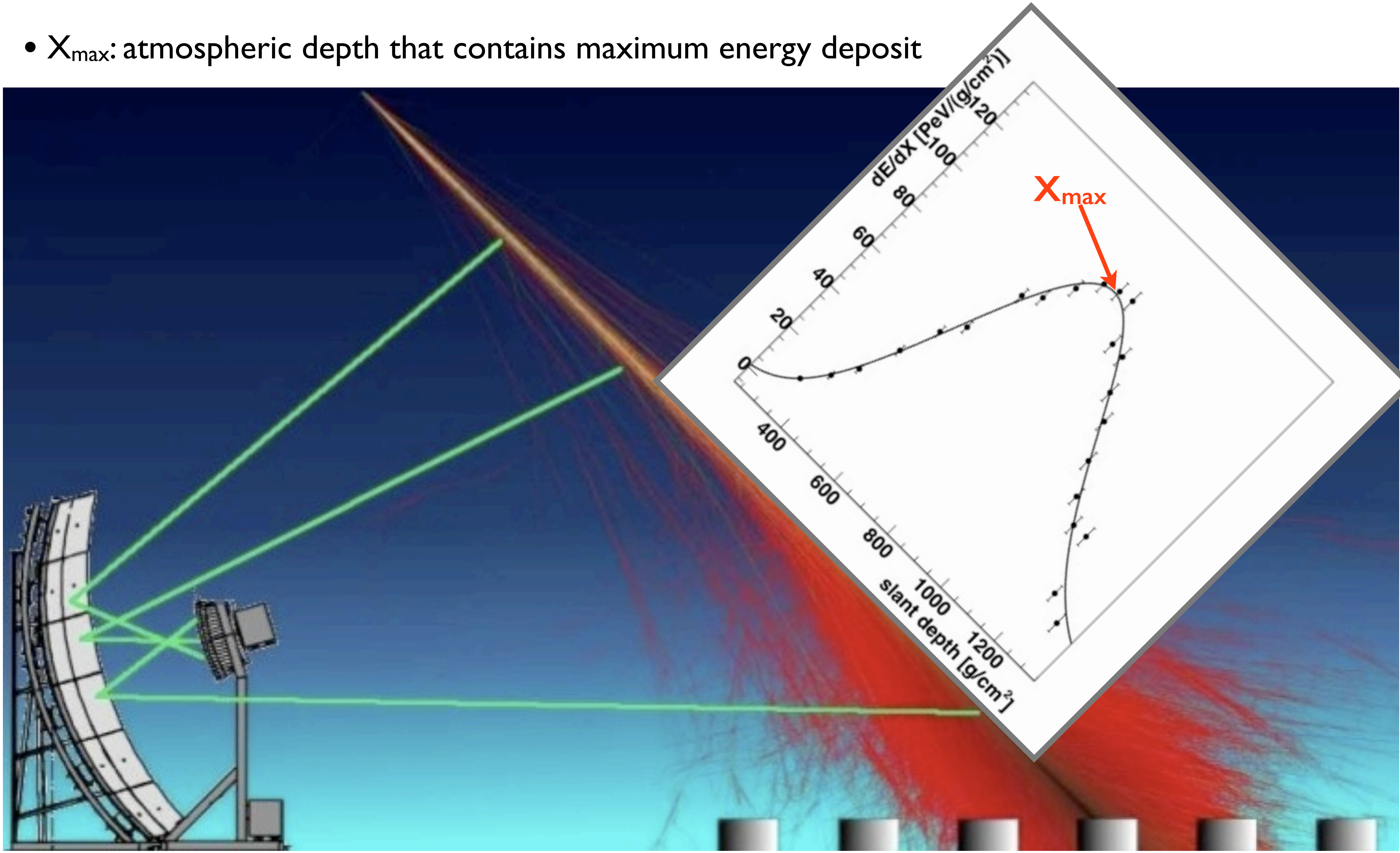
SDs: 100% duty cycle, measure particle density

Observation with the fluorescence detector



Observatory for hybrid detection

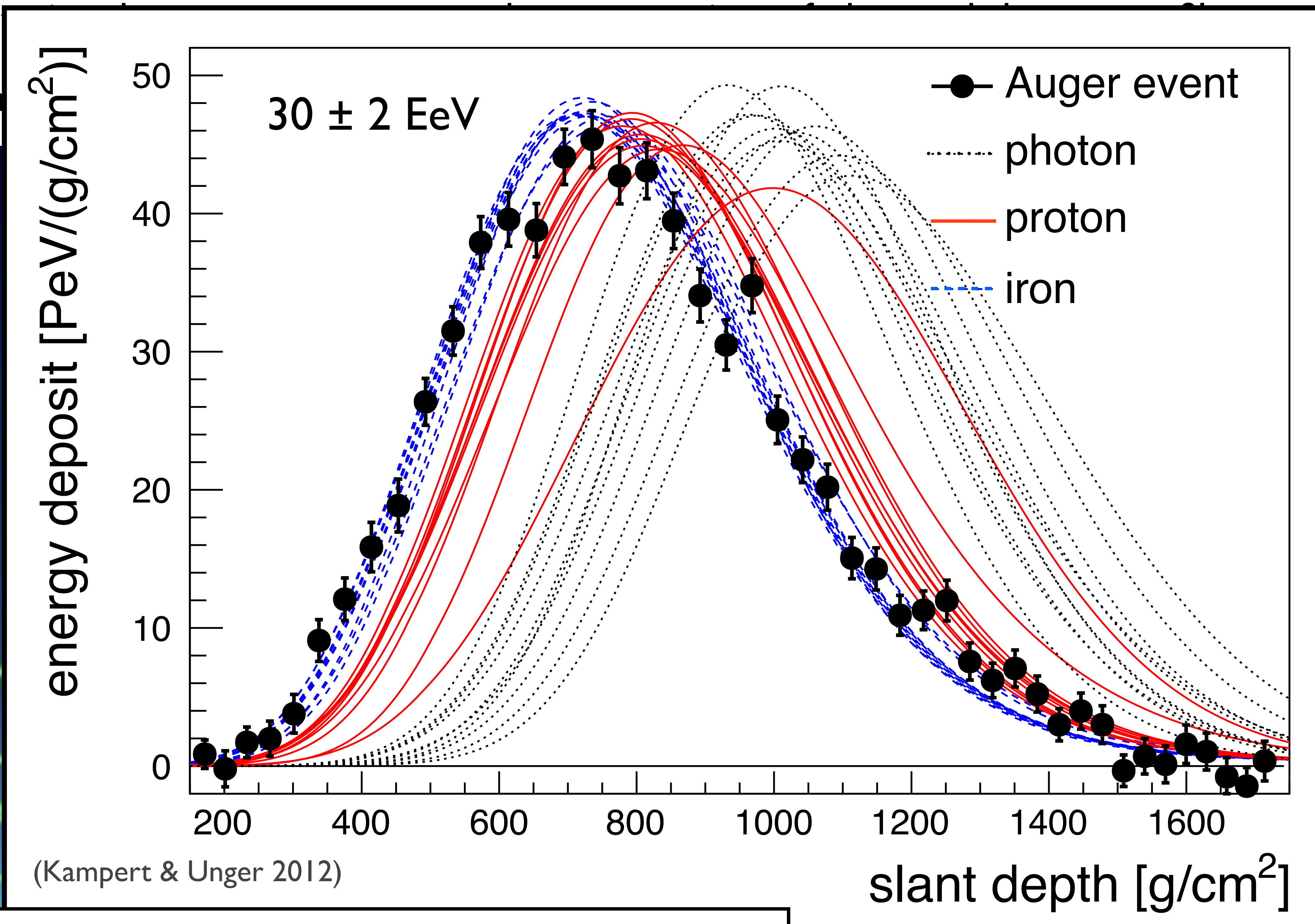
- SD constrains shower geometry → reduce uncertainty of observed shower profile
- X_{max}: atmospheric depth that contains maximum energy deposit



(slant depth: air mass along cosmic ray trajectory)

Observatory for hybrid detection

- SD cons
- X_{max}: atn



(Kampert & Unger 2012)

Proton primaries develop deeper in the atmosphere with larger fluctuations than heavier nuclei (e.g. Fe nuclei)

(slant depth: air mass along cosmic ray trajectory)

Data selection

December 2004 - December 2012

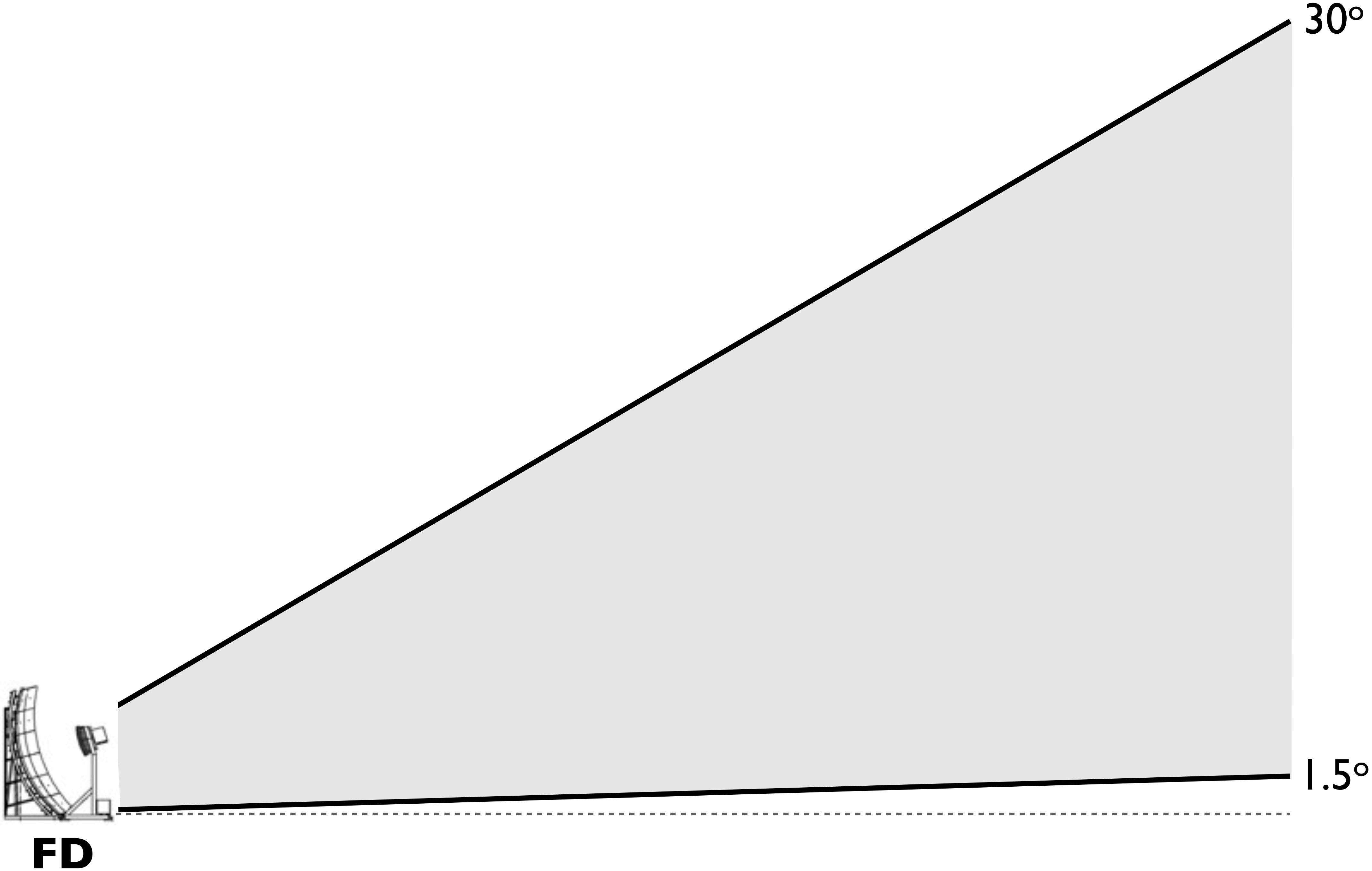
TABLE I. Event selection criteria, number of events after each cut and selection efficiency with respect to the previous cut.

Cut	Events	ε [%]
Pre-selection:		
Air-shower candidates	2573713	$\cdots$
Hardware status	1920584	74.6
Aerosols	1569645	81.7
Hybrid geometry	564324	35.9
Profile reconstruction	539960	95.6
Clouds	432312	80.1
$E > 10^{17.8}$ eV	111194	25.7
Quality and fiducial selection:		
P(hybrid)	105749	95.1
X_{max} observed	73361	69.4
Quality cuts	58305	79.5
Fiducial field of view	21125	36.2
Profile cuts	19947	94.4

Combine showers observed at more than: **19,759**
one FD site (stereo, triple, quadruple)

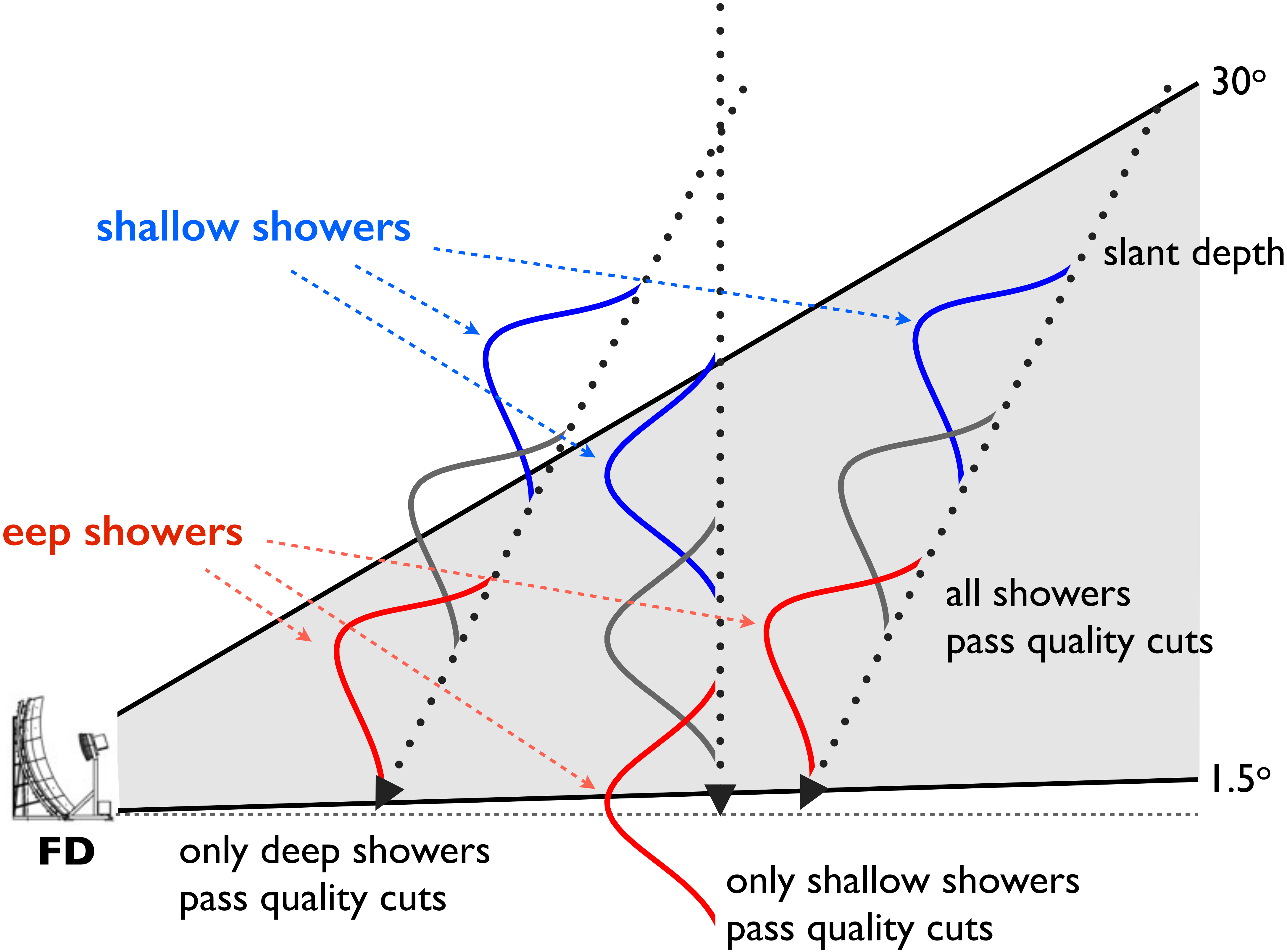
Field of View

➡ Prevent bias to event selection



Field of View

➡ Prevent bias to event selection



19,759 events:

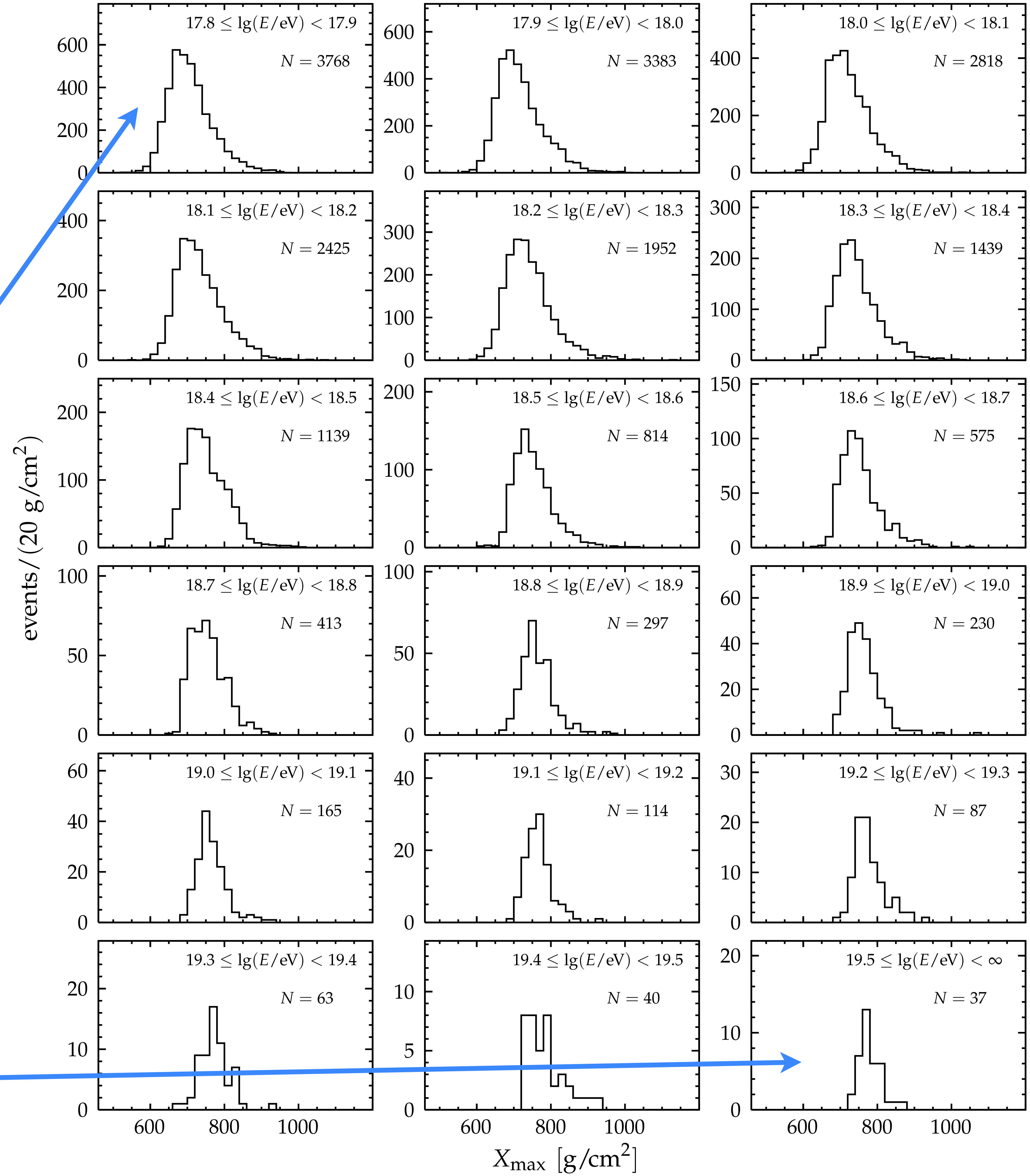
for the first time in cosmic ray history, the *full distribution* of X_{max} has been obtained.

log(E/eV) = 17.8-17.9

No. events: 3768

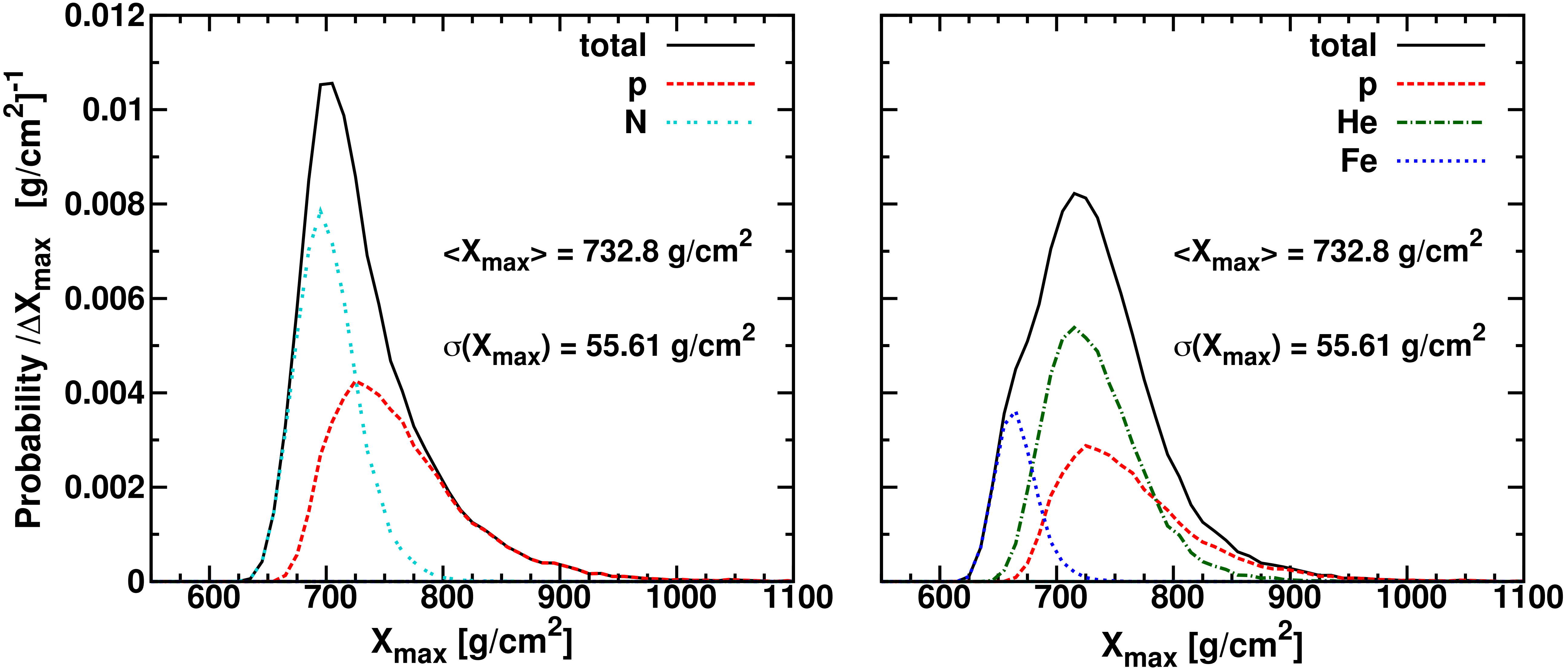
log(E/eV) ≥ 19.5

No. events: 37



Reasons to use the X_{max} distribution

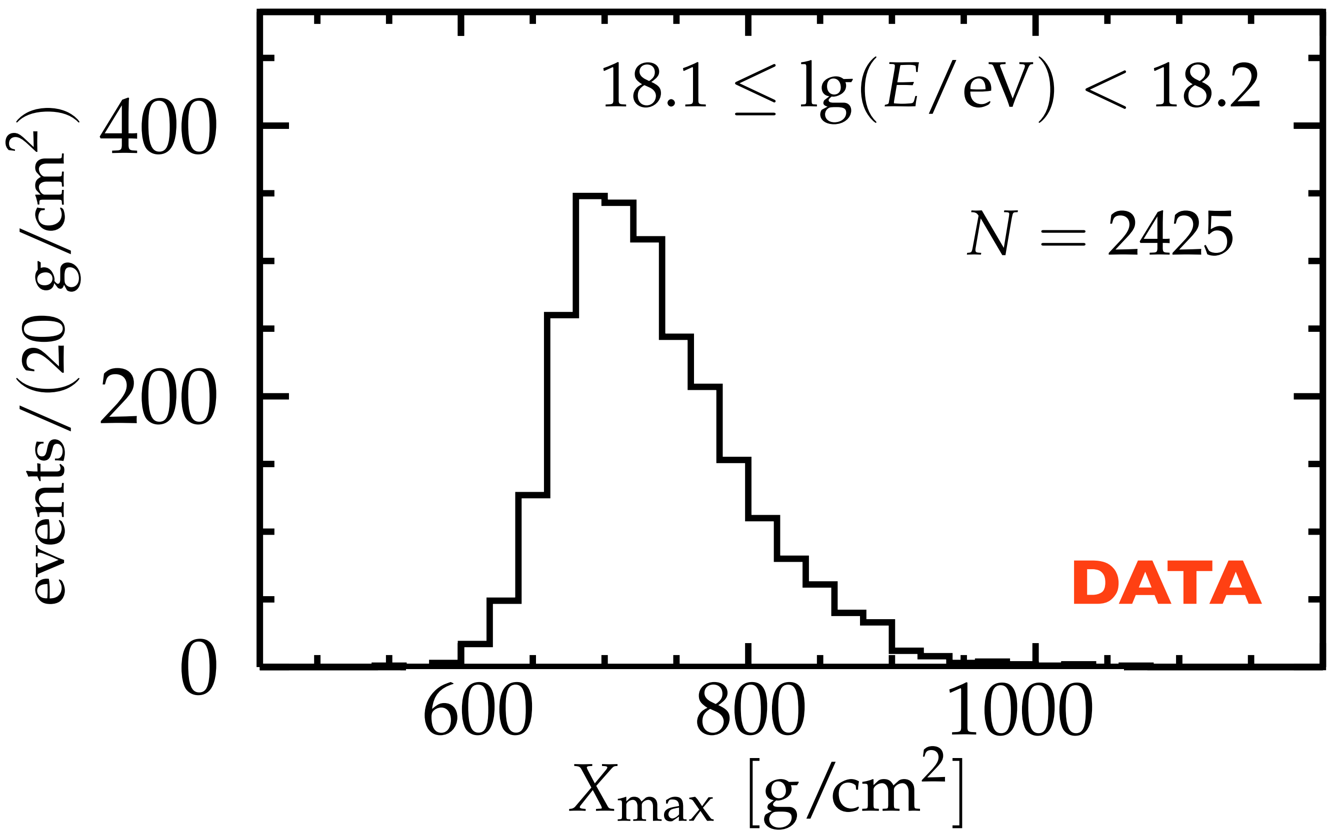
Different composition: identical first two moments, different distribution

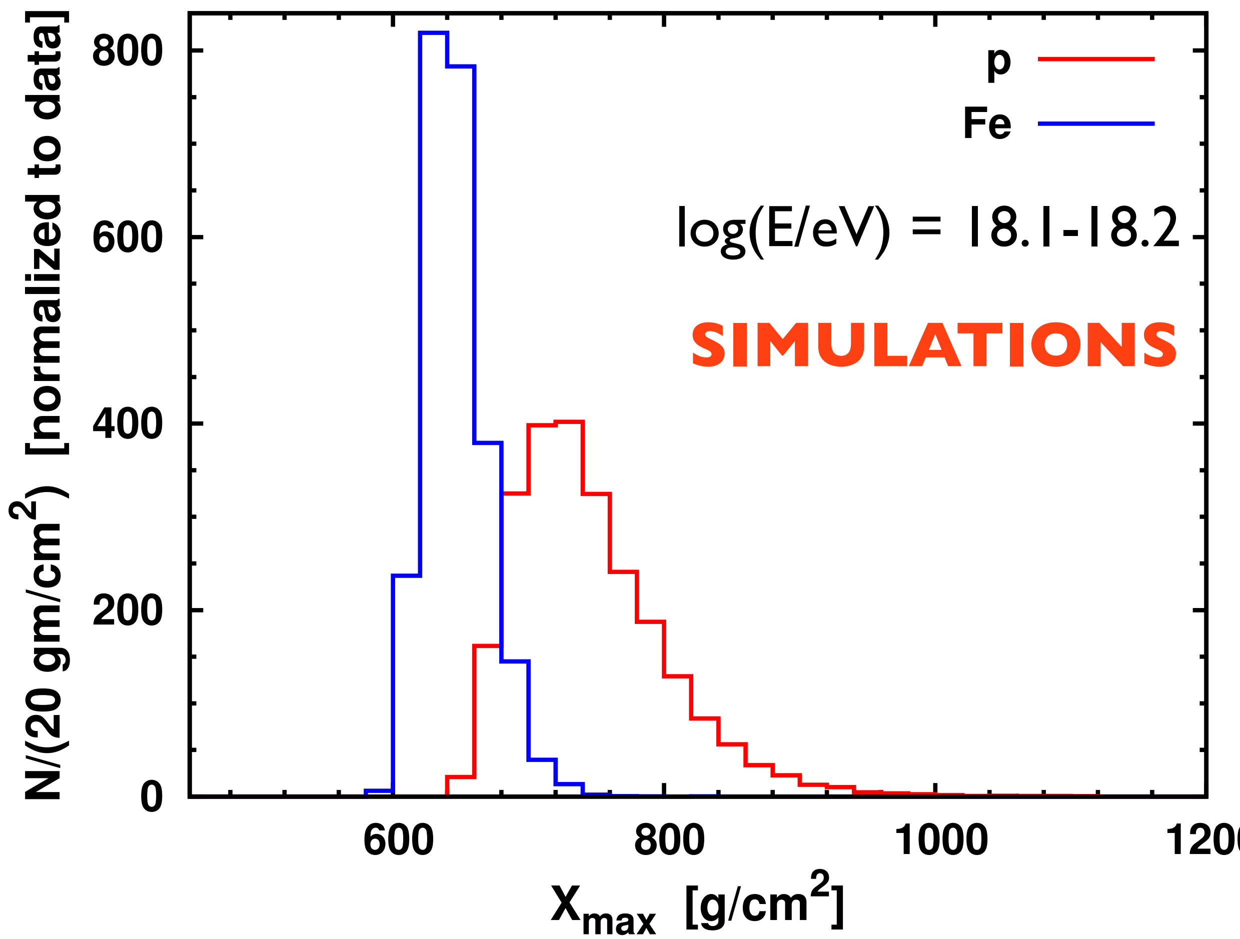


- No degeneracy in untangling mass combination
- Better understanding of composition
- Information on hadronic interaction models (particle physics at $E_{CM} \gtrsim 35$ TeV)

Find composition of UHECRs from the X_{max} distributions

- Compare data to simulations

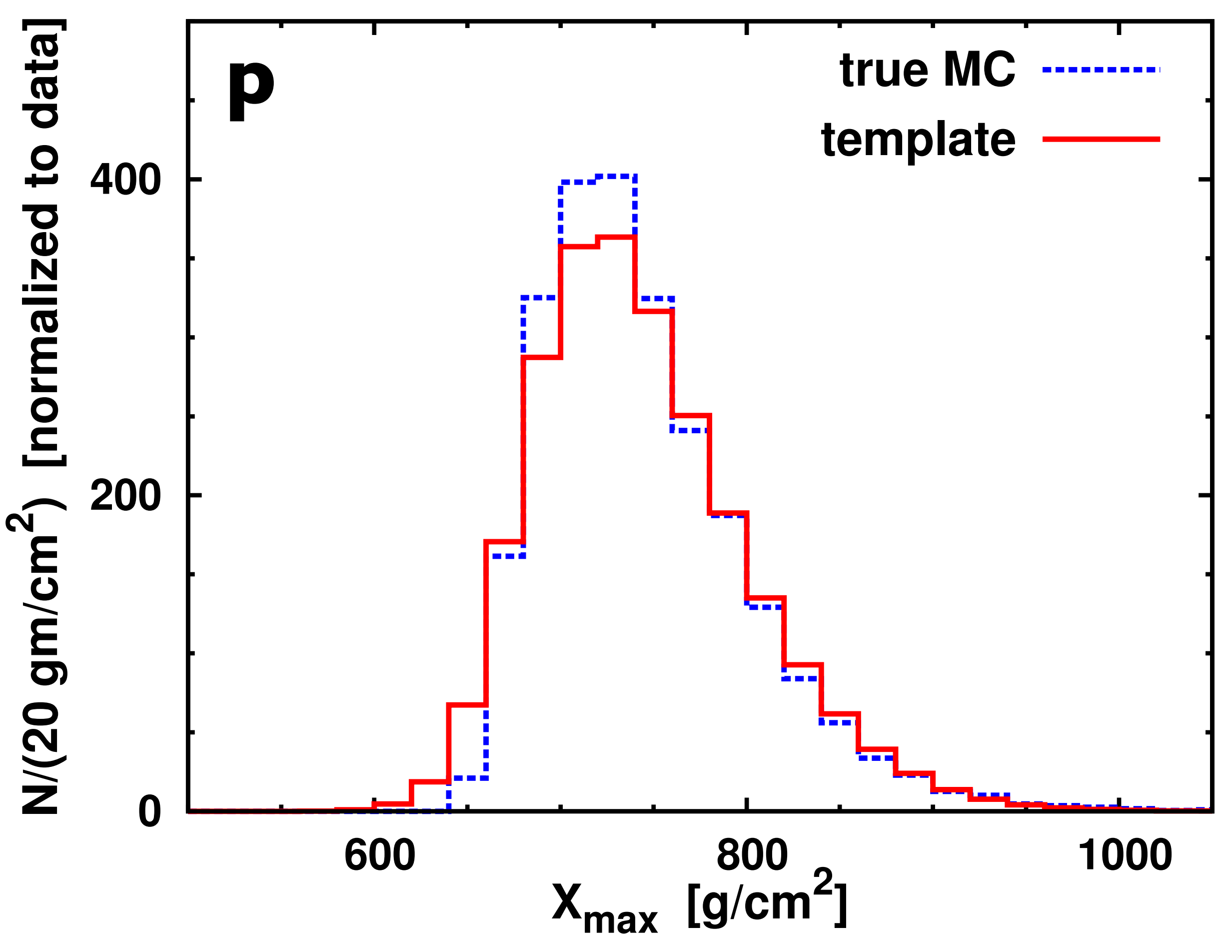


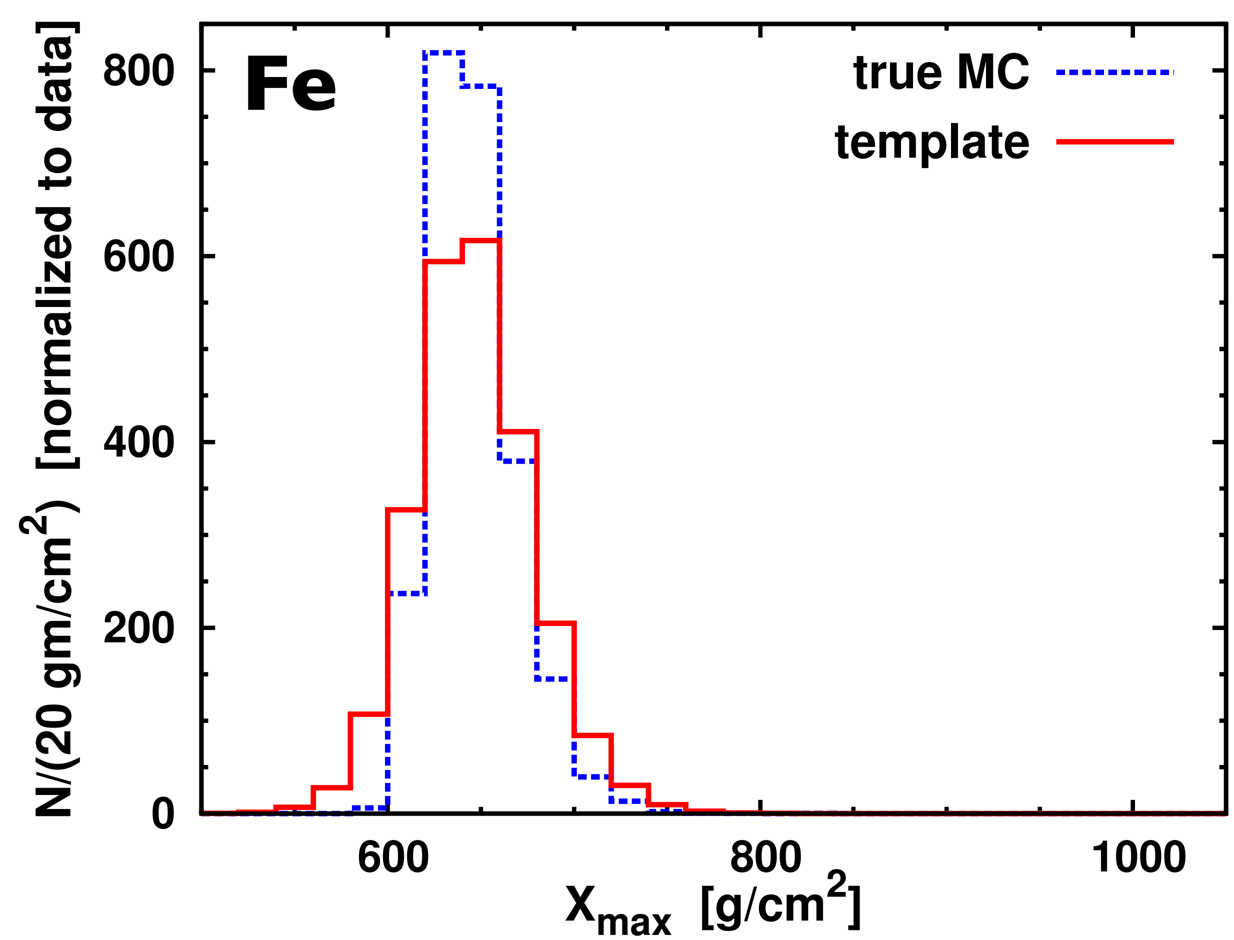


- Simulations mimic true X_{max} distribution
- We do not observe the true X_{max} distribution
  - detector acceptance across X_{max} FOV
  - position determination affected by resolution ability
- Create templates that can be properly compared with the data
  - modify the simulations so they become "observations"

Making of a template

1. Generate MC for each energy bin, species, hadronic interaction models;
   - 18 energy bins from $E=10^{17.8}$ eV to $E \geq 10^{19.5}$ eV
   - species: p, He nucleus, N nucleus, Fe nucleus
   - hadronic interaction models: EPOS-LHC, QGSJET II-4, Sibyll 2.1
   - 20,000 events each
2. Fold in acceptance and detector smearing matrix to the true X_{max} distribution;
3. Create template for each species under consideration, combine to form MC prediction.





Fitting template to data

- Find best fitting species combination via binned likelihood
  - for *j*-th X_{max} bin, compare MC prediction C_j with data n_j

$$\boxed{L = \prod_j \frac{e^{-C_j} C_j^{n_j}}{n_j!}} \xrightarrow{\text{likelihood ratio}} \boxed{\prod_j \left[\frac{e^{-C_j} C_j^{n_j}}{n_j!}\right] \Big/ \left[\frac{e^{-n_j} n_j^{n_j}}{n_j!}\right]}$$

goodness of fit estimator

- Goodness of fit: obtain *p*-value with MC-based method
  - find best fit from data → generate mock data sets based on this fit
  - *p*-value = fraction of mock data sets with worse fit than fit from real data

- Systematics: consider systematic uncertainty from measurement
  - measured X_{max} (scan between -1σ to +1σ)
  - energy scale
  - X_{max} resolution
  - acceptance

  } refit data with extreme values of the parameterizations

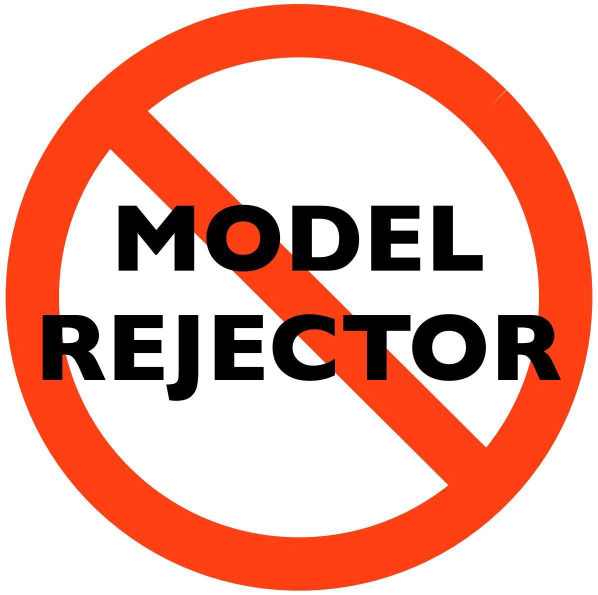
  ↳ encompass full range of values obtained by any of the fit variants

  p-values also calculated

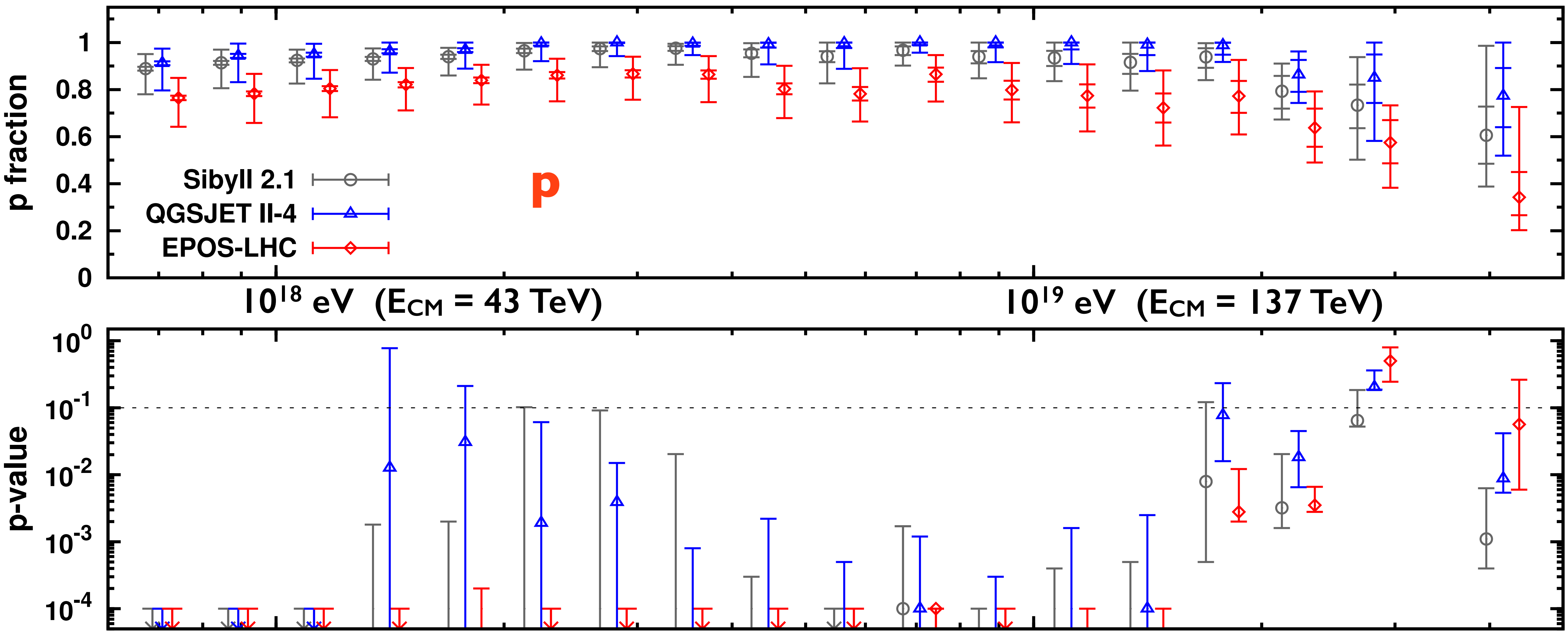
Fit results

CAUTION! Results are dependent on the hadronic interaction models

Modification of the models may lead to changes



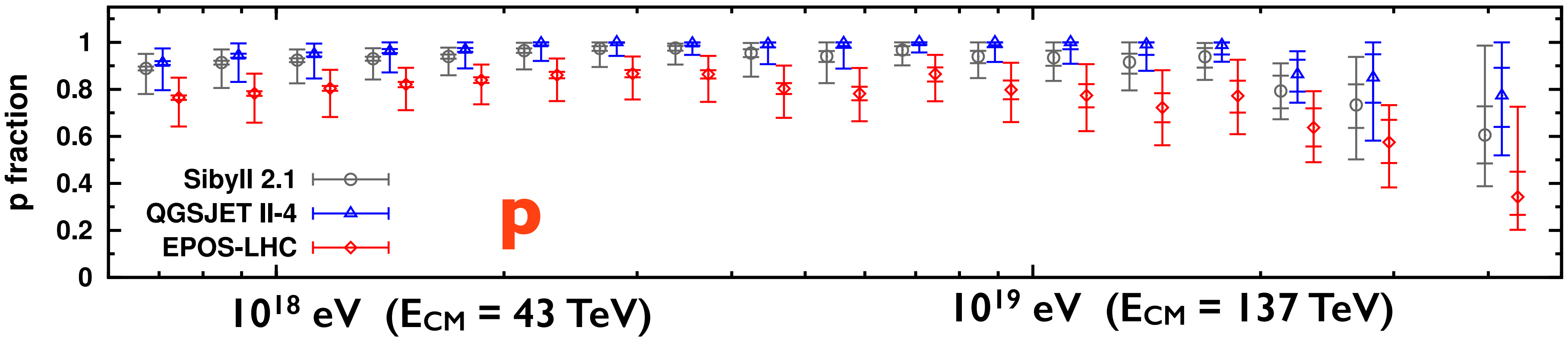
p + Fe hypothesis

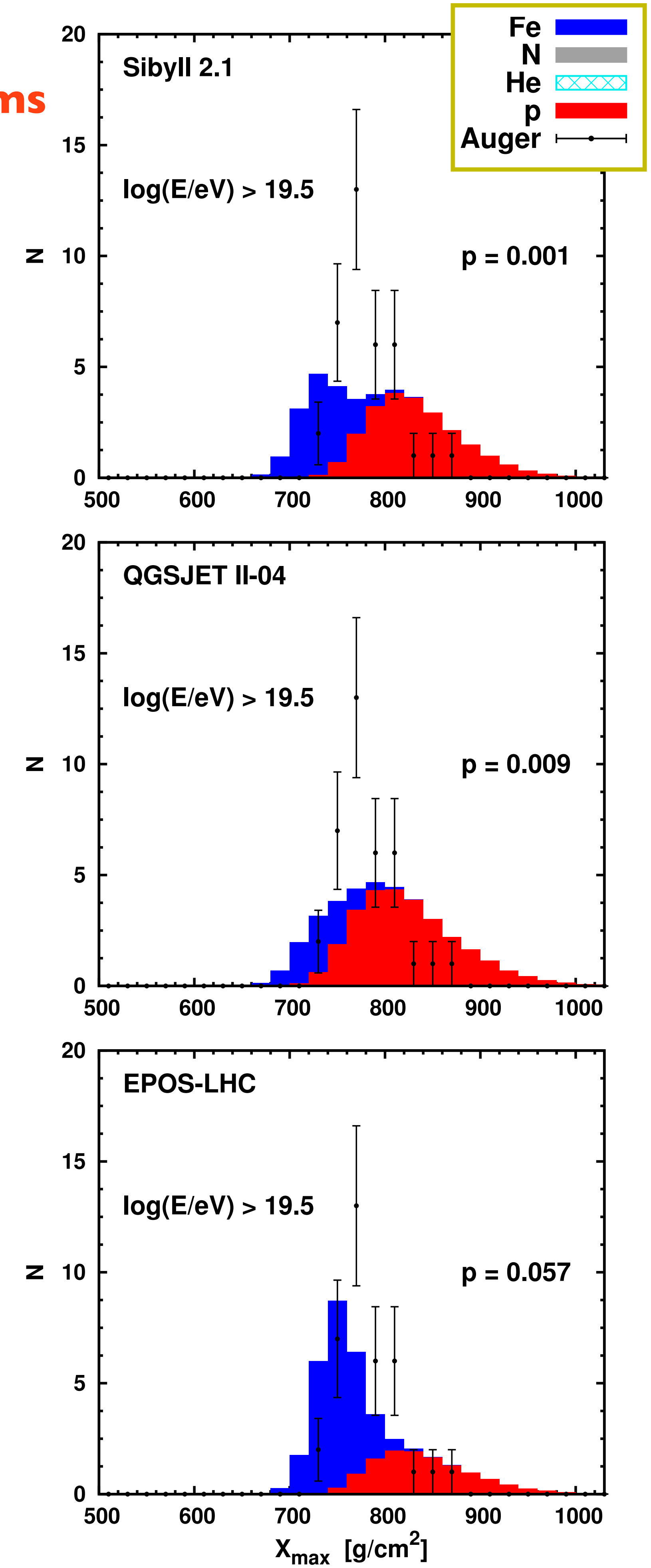


- Mostly to mainly protons for E < 10^{19} eV
- Poor quality fit: hadronic interaction models cannot describe data with p & Fe
  - ➡ hypothesis of **only p and Fe not feasible** - something else required

Lack of Fe nuclei

Stacked histograms



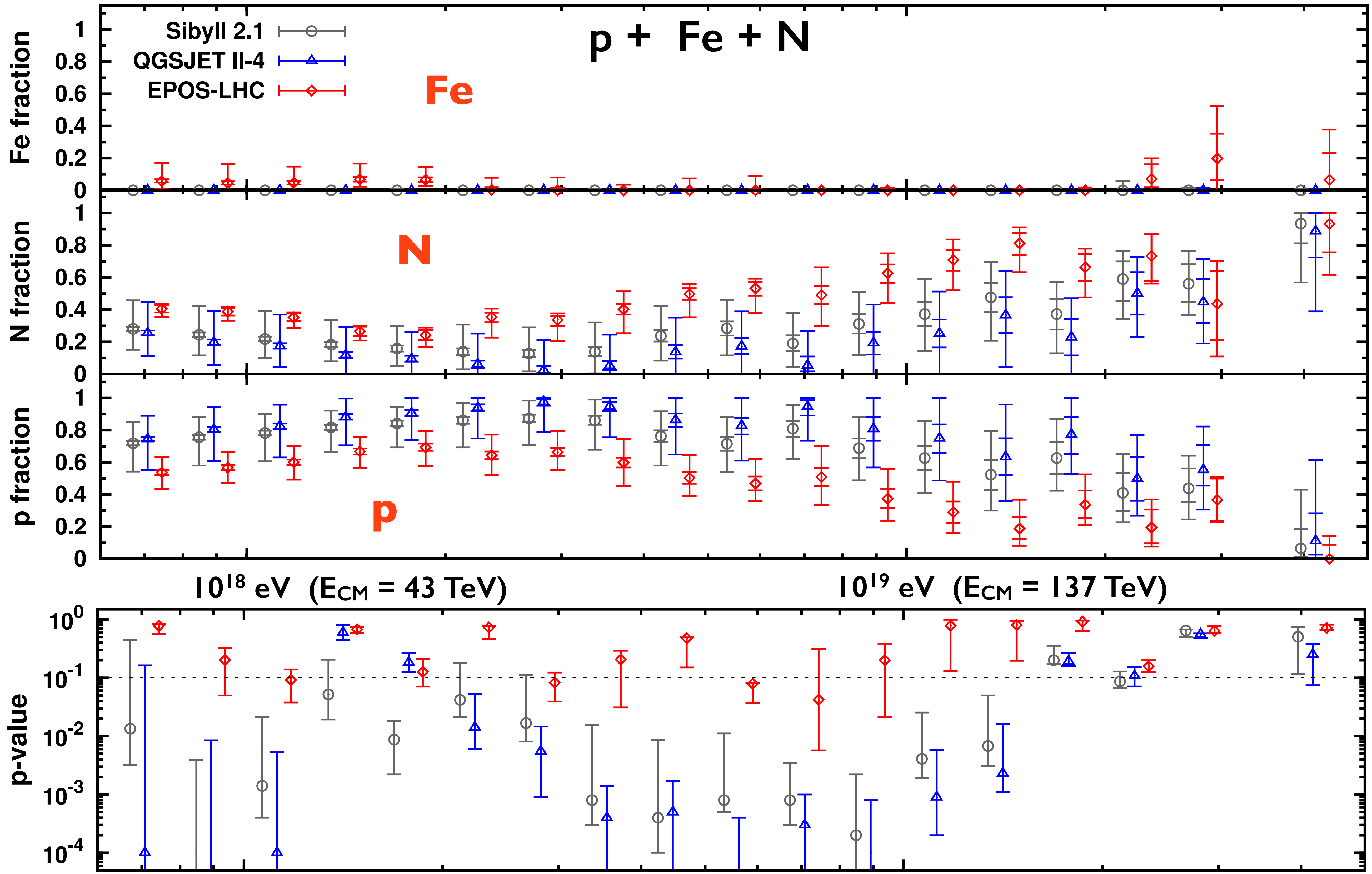


Fe distribution:

- too shallow (small X_{max})
- peaks at smaller X_{max} than data
- wider than data

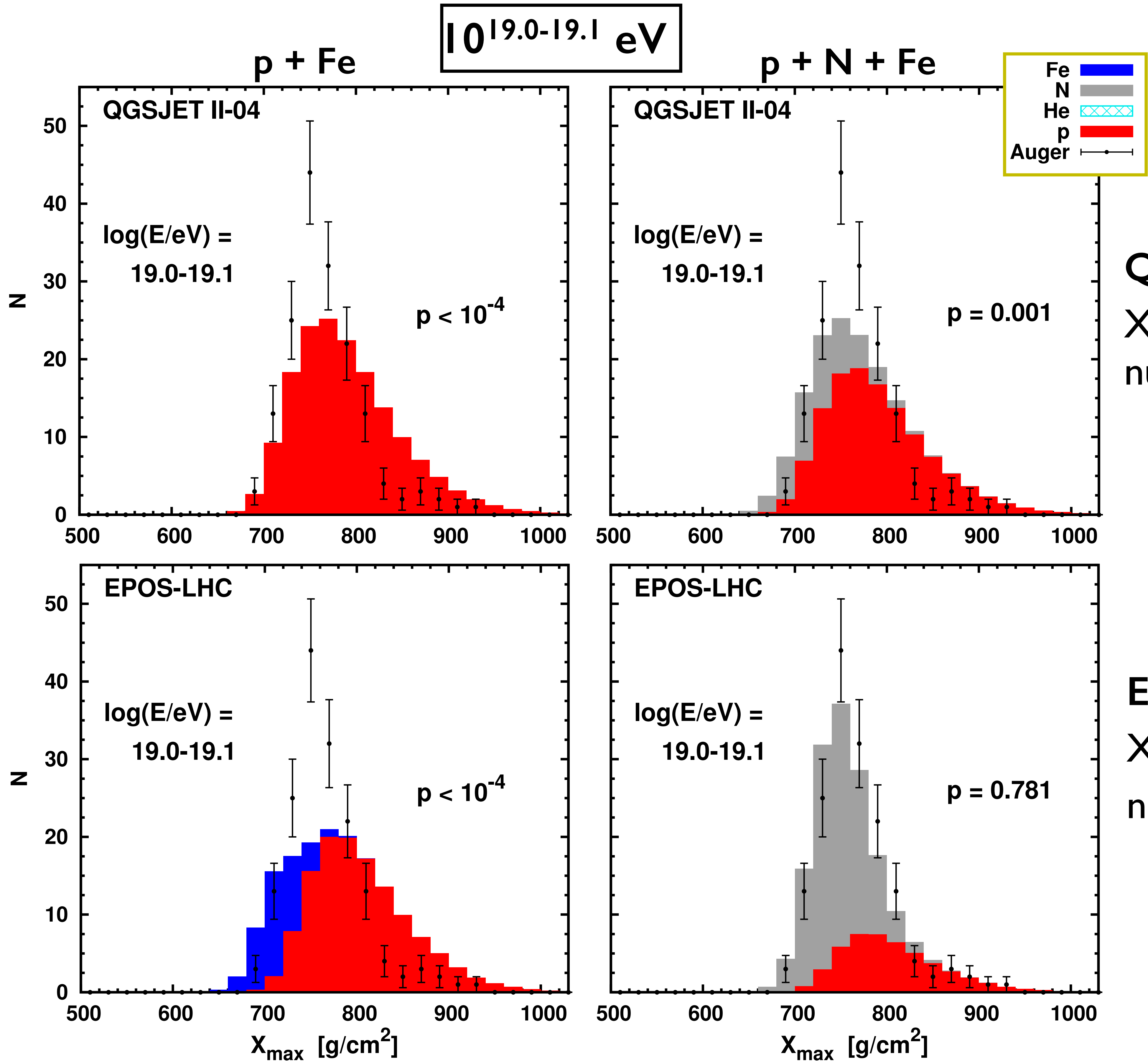
} for all models considered

➡ Data need a distribution that is **deeper** (larger X_{max}) and **narrower**



- Better fit quality for EPOS-LHC, but not for Sibyll 2.1 & QGSJET II-4

Inclusion of an intermediate mass nucleus



QGSJET II-04:

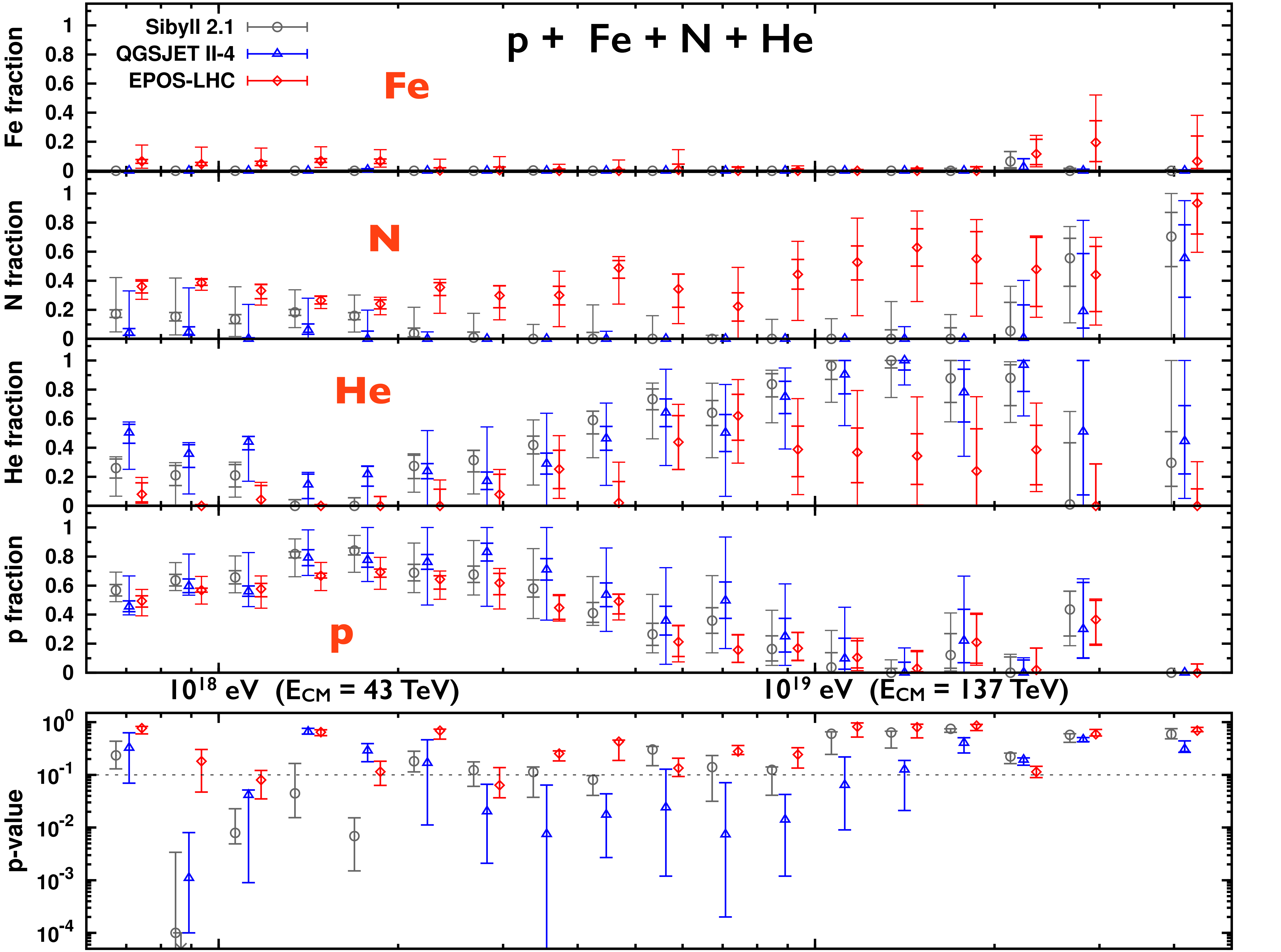
X_{max} distribution of N nuclei is too shallow

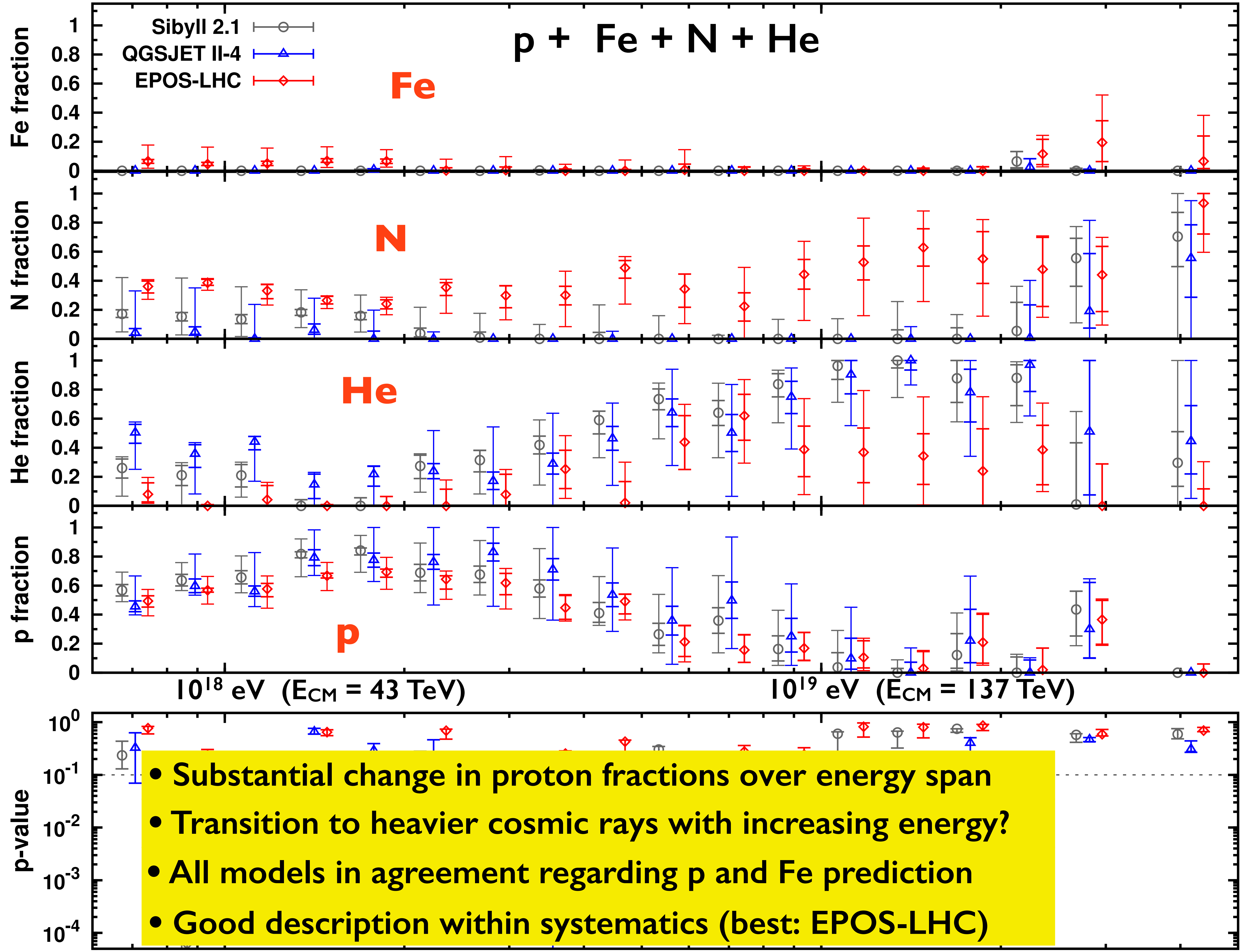
→ cannot describe data

EPOS-LHC:

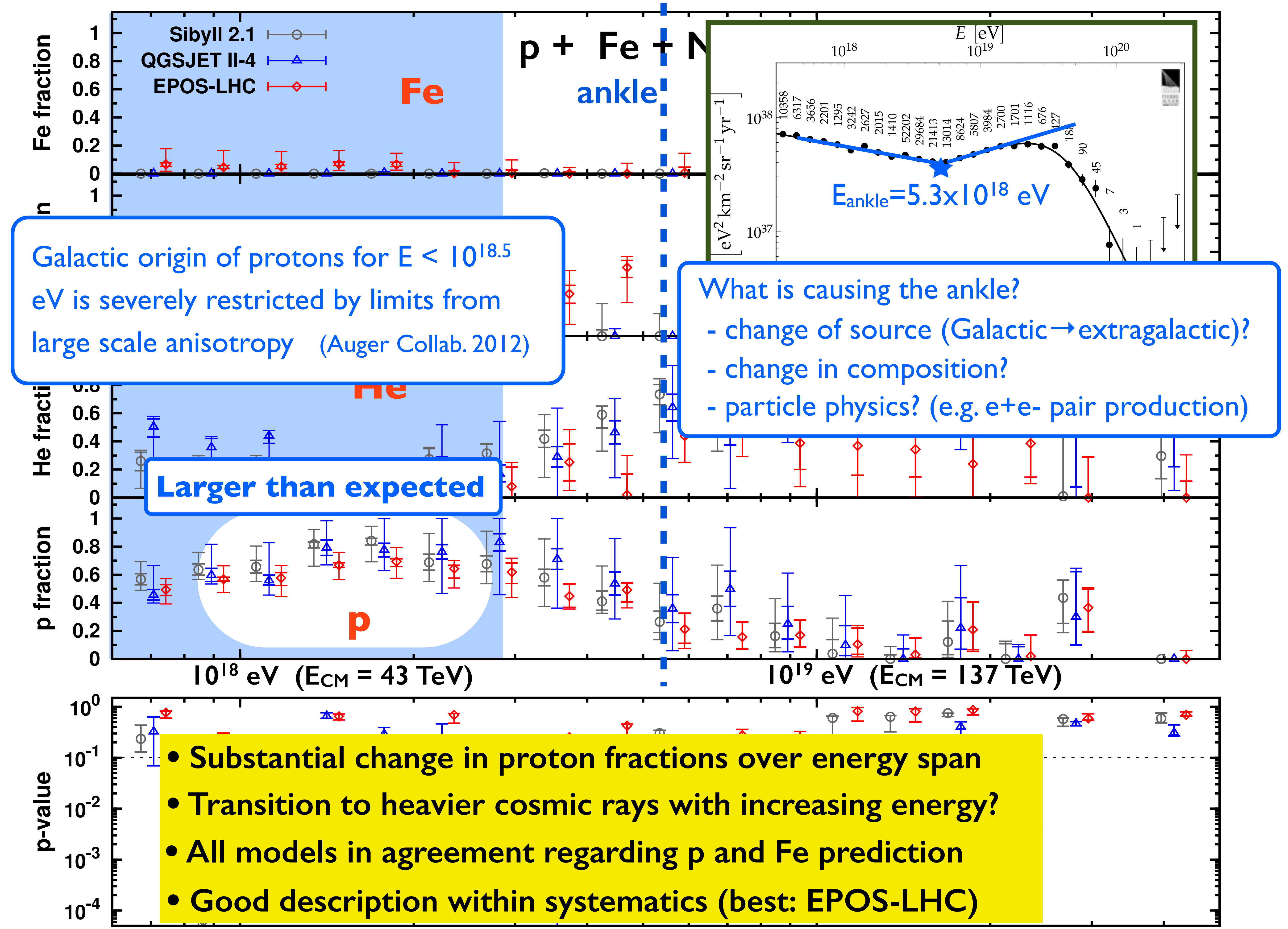
X_{max} distribution of N nuclei is at the right place!

→ satisfactory fit


p + Fe + N + He
Sibyll 2.1
QGSJET II-4
EPOS-LHC
Fe
N
He
p
Fe fraction
N fraction
He fraction
p fraction
p-value
10^18 eV (E_CM = 43 TeV)
10^19 eV (E_CM = 137 TeV)

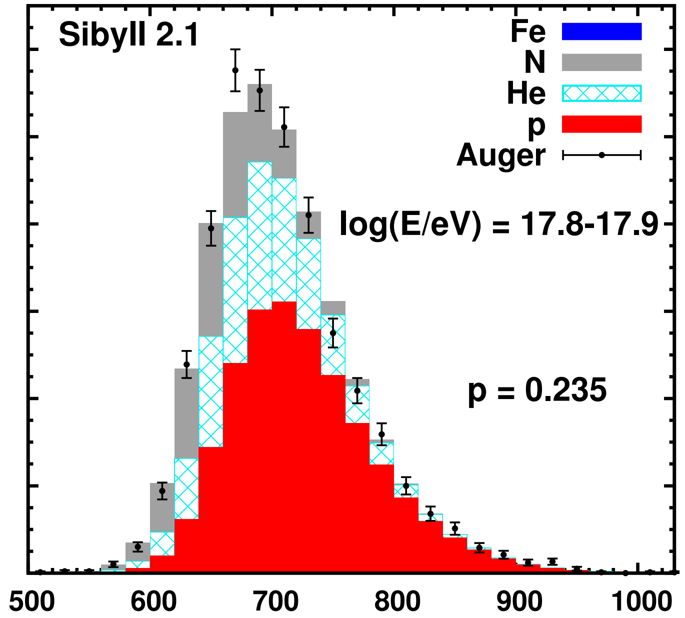


- Substantial change in proton fractions over energy span
- Transition to heavier cosmic rays with increasing energy?
- All models in agreement regarding p and Fe prediction
- Good description within systematics (best: EPOS-LHC)

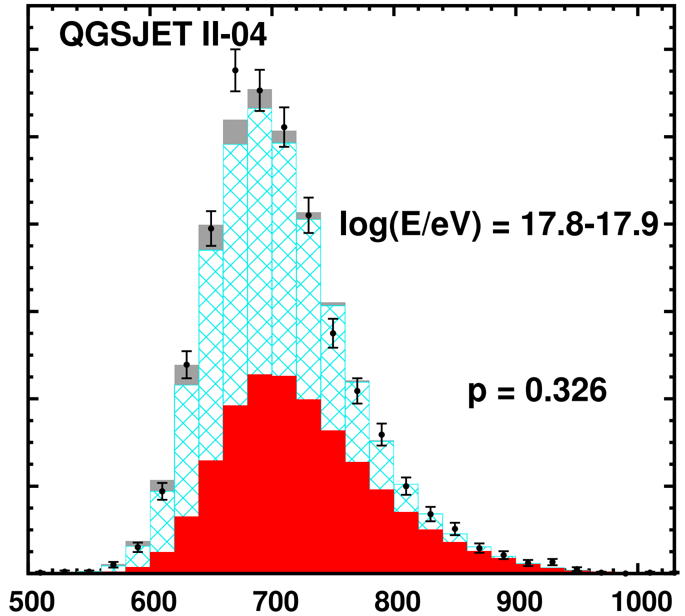

Sibyll 2.1
QGSJET II-4
EPOS-LHC
Fe fraction
Fe
p + Fe + N
ankle
He fraction
He
p fraction
p
p-value
10^18 eV (E_CM = 43 TeV)
10^19 eV (E_CM = 137 TeV)
E [eV]
E_ankle=5.3x10^18 eV
Galactic origin of protons for E < 10^18.5 eV is severely restricted by limits from large scale anisotropy (Auger Collab. 2012)
What is causing the ankle?
- change of source (Galactic→extragalactic)?
- change in composition?
- particle physics? (e.g. e+e- pair production)
Larger than expected
• Substantial change in proton fractions over energy span
• Transition to heavier cosmic rays with increasing energy?
• All models in agreement regarding p and Fe prediction
• Good description within systematics (best: EPOS-LHC)

$10^{17.8\text{-}17.9}$ eV

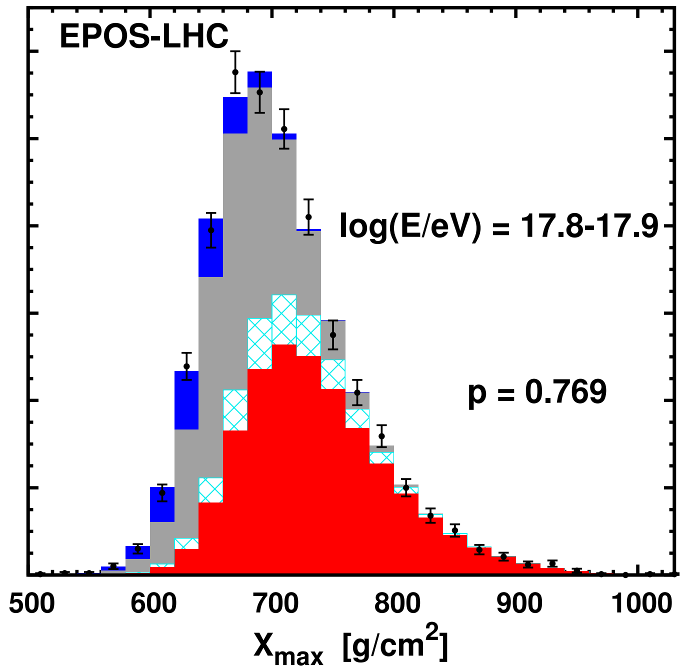
Sibyll 2.1



QGSJET II-04



EPOS-LHC



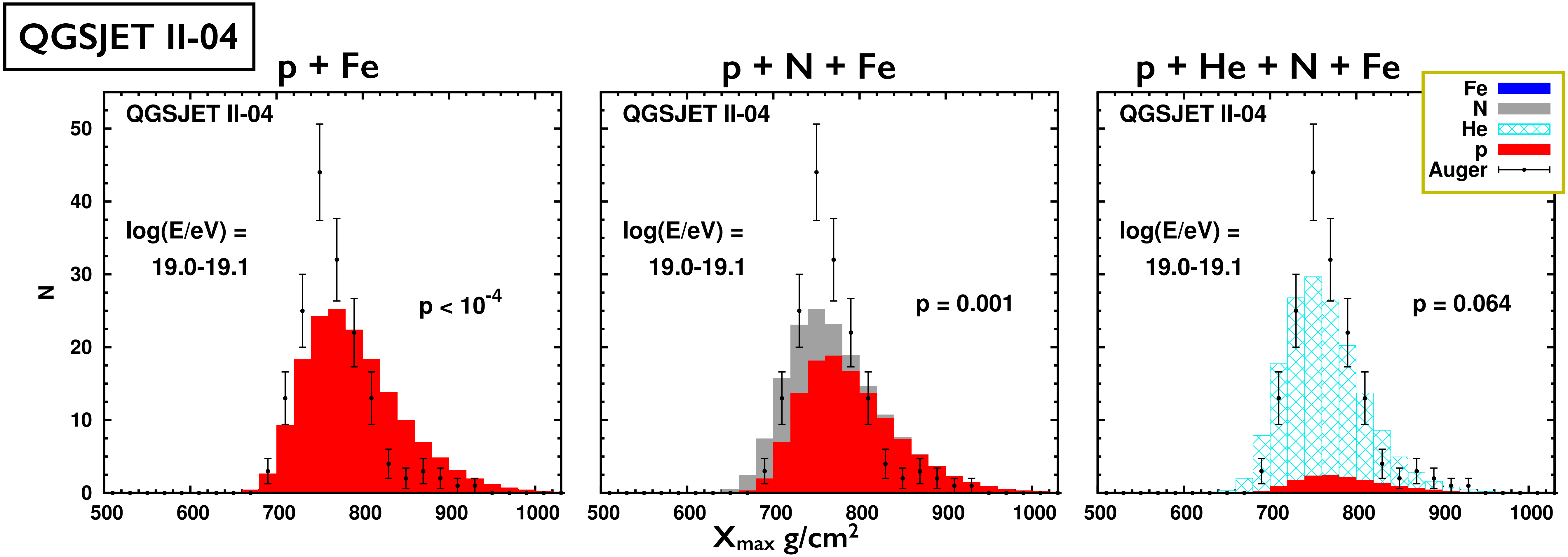
Fits can have different composition combinations, yet ...

- Similar p and Fe fraction
- Similar He+N fraction
- Amount of He and N varies

Each hadronic interaction model differs in how the air shower develops (cross section, multiplicity, elasticity) & evolve differently with increasing nucleus mass.

	p	He	N	Fe
Sibyll 2.1	0.57	0.26	0.17	0.00
QGSJET II-04	0.46	0.50	0.04	0.00
EPOS-LHC	0.49	0.08	0.36	0.07

Constrain hadronic interaction models



- **p+Fe:** Fe distribution is too shallow for data,
  p distribution cannot cover peak or head region
- **p+N+Fe:** N distribution covers head region but still cannot fit well
- **p+He+N+Fe:** data prefers mostly He, but cannot describe data adequately

➡ Data prefers p & He - poor fit quality

➡ No possible realistic species can make better - this **model requires modification**

To recapitulate;

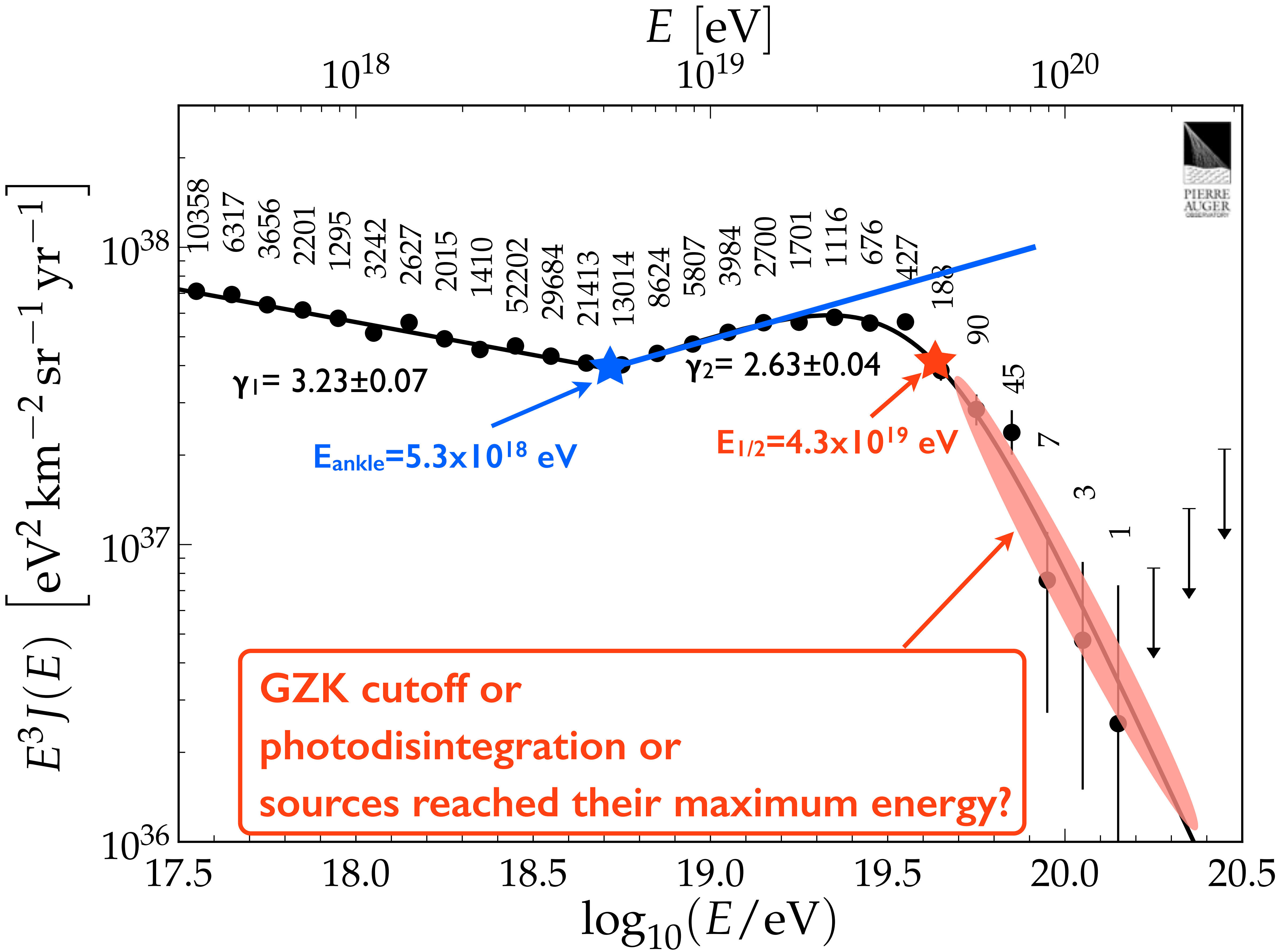
Between 7×10^{17} eV to 4×10^{19} eV,

- Surprise #1
  - ➡ Hypothesis of **"p and Fe only" does not work!!**
    Substantial presence of **intermediate** species required!!
  - ➡ No or very little p and Fe at highest energy bin

- Surprise #2
  - ➡ Considerable presence of protons below "ankle" (5×10^{18} V)
    - unexpected due to large scale anisotropy limits; pose some constraints in explaining presence of ankle

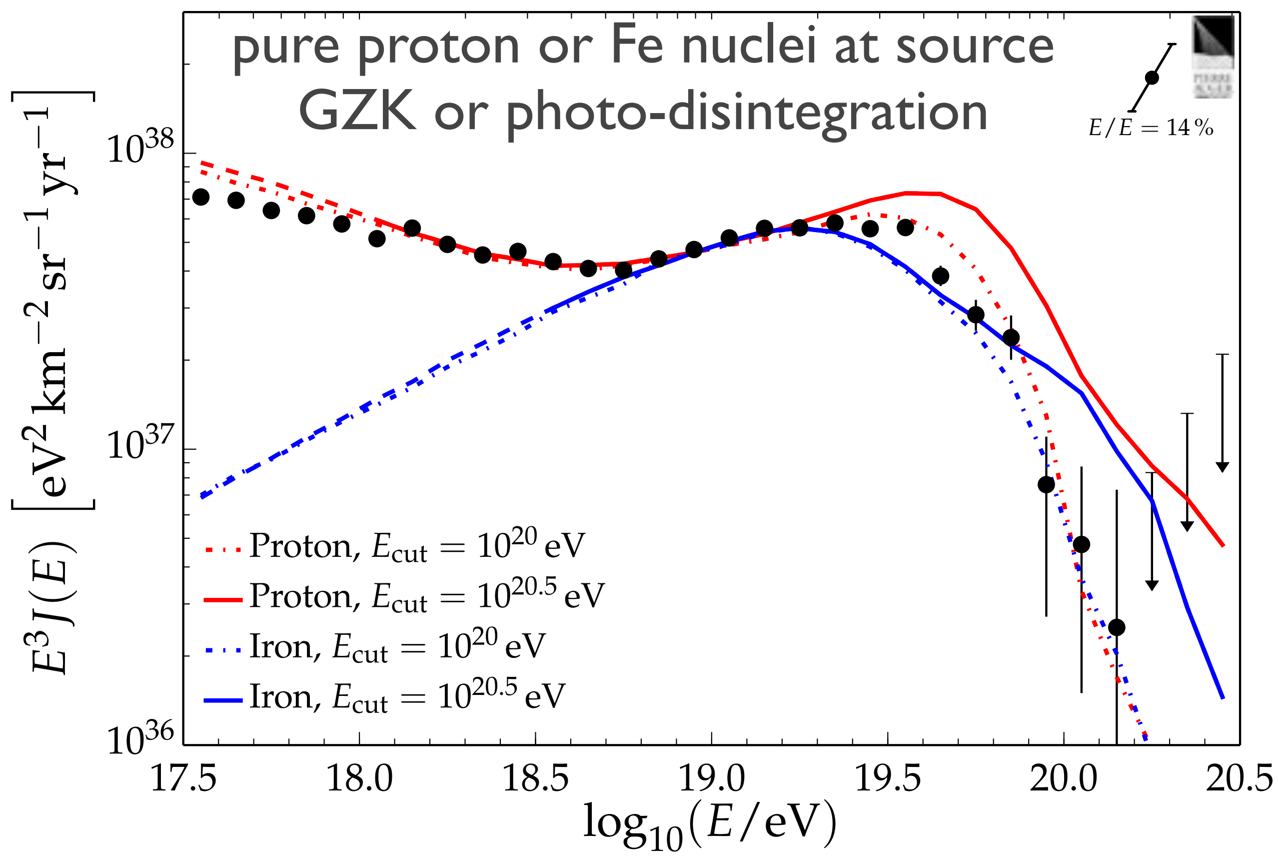
- Understand better and constrain hadronic interaction models
  - ➡ X_{max} distribution shows why some species do or do not work
  - ➡ constrain model when varying or increasing species do not work

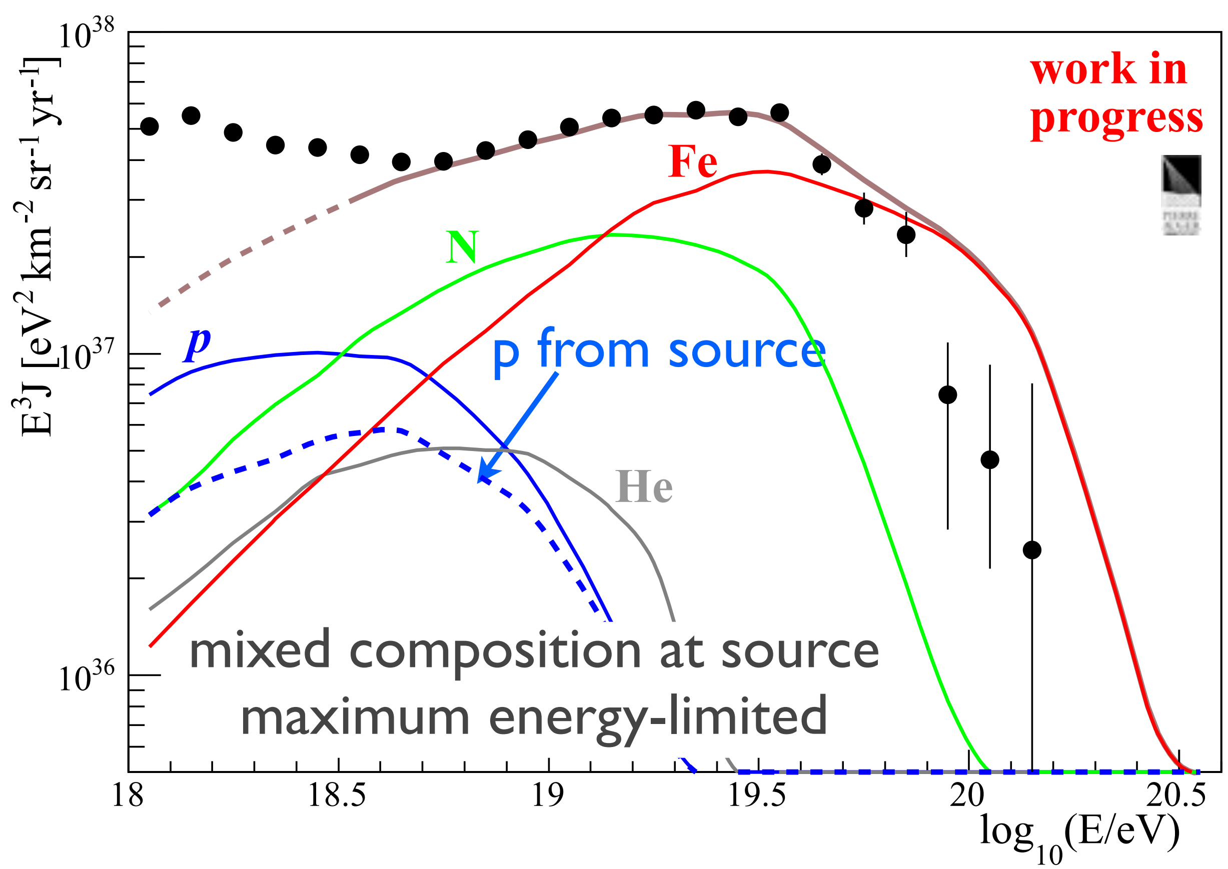
Energy spectrum - what is causing the suppression?



What is the reason for the flux suppression?

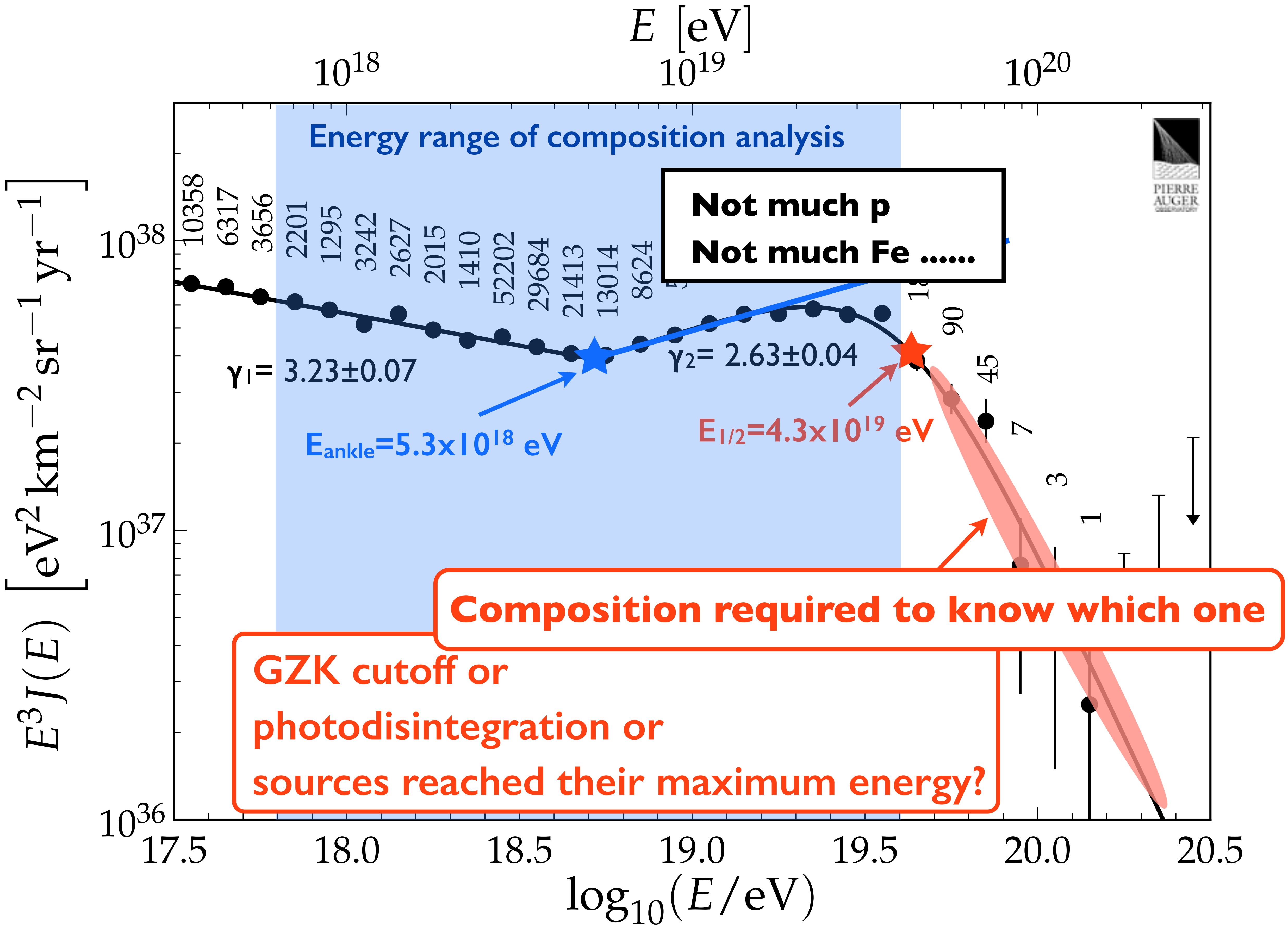
- GZK cutoff → **extragalactic protons** (Berezinsky & Grigoreva 1988 etc.)
- Photodisintegration of heavy nuclei → **extragalactic proton & nuclei** (Taylor, et al 2011 etc.); **Galactic and extragalactic nuclei** (Hillas 1984; Fang et al 2013 etc.)
- Limited energy at source → **extragalactic proton & nuclei** (Allard et al. 2008 etc.)



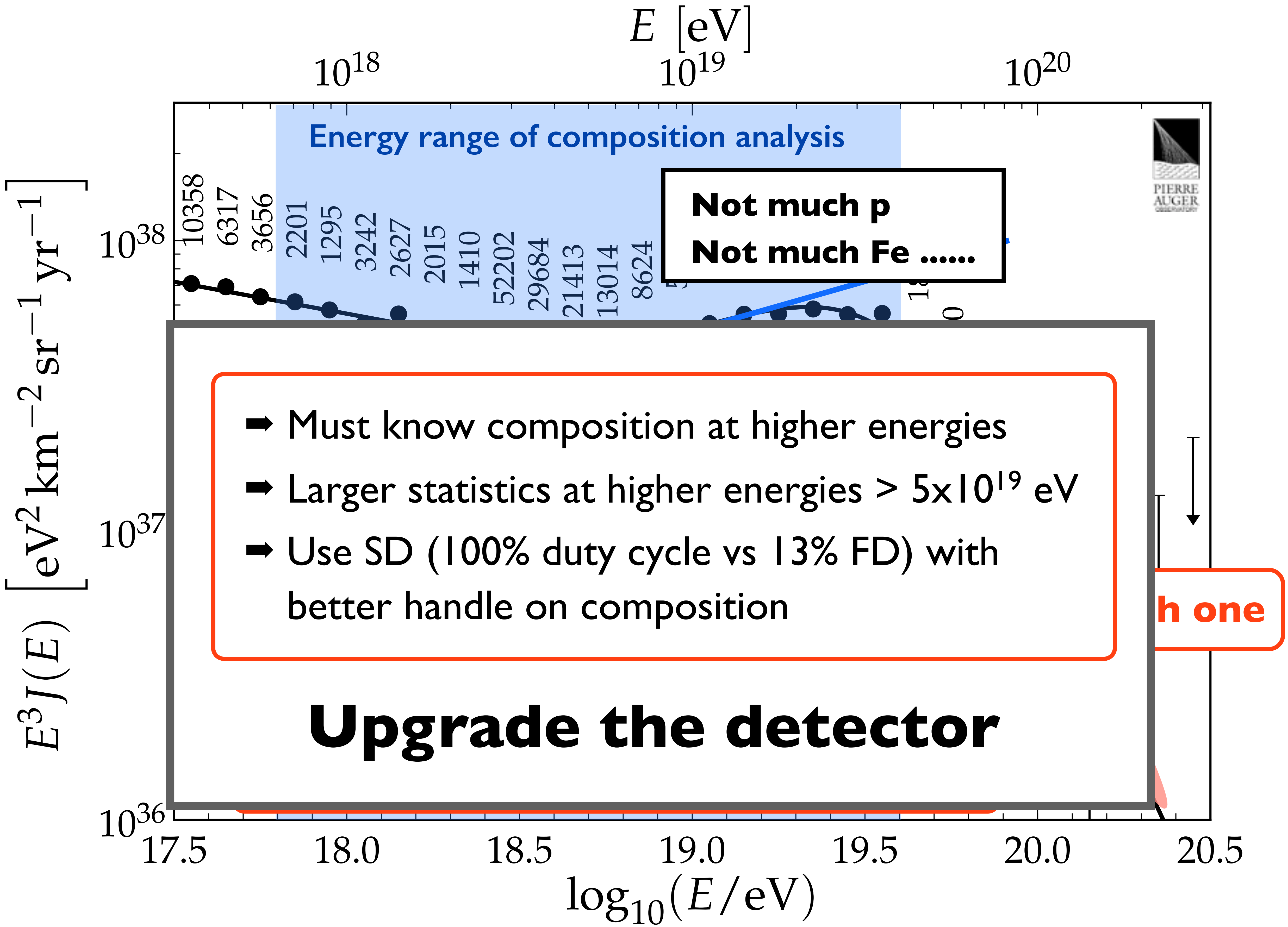


➡ Knowing composition is the key to understanding the flux suppression

Energy spectrum - what is causing the suppression?



Energy spectrum - what is causing the suppression?



Not much p

Not much Fe ......

- ➡ Must know composition at higher energies
- ➡ Larger statistics at higher energies > 5×10^{19} eV
- ➡ Use SD (100% duty cycle vs 13% FD) with better handle on composition

Upgrade the detector

Science goals of the Auger upgrade

1. Elucidate origin of flux suppression and mass composition;

- differentiate between the energy loss due to propagation (e.g. GZK suppression) and the maximum energy of particles at source
- Galactic or extragalactic origin?
- reliable estimates of propagation-induced neutrino and gamma ray flux

2. Search for contribution of protons at the highest energy

- estimate physics potential of existing and future CR, neutrino, gamma-ray detectors
- determine prospect for proton astronomy (open a new window or not?)
- predict propagation-induced neutrino and gamma ray fluxes

3. Study hadronic interactions and extensive air showers above $E_{CM} > 70$ TeV

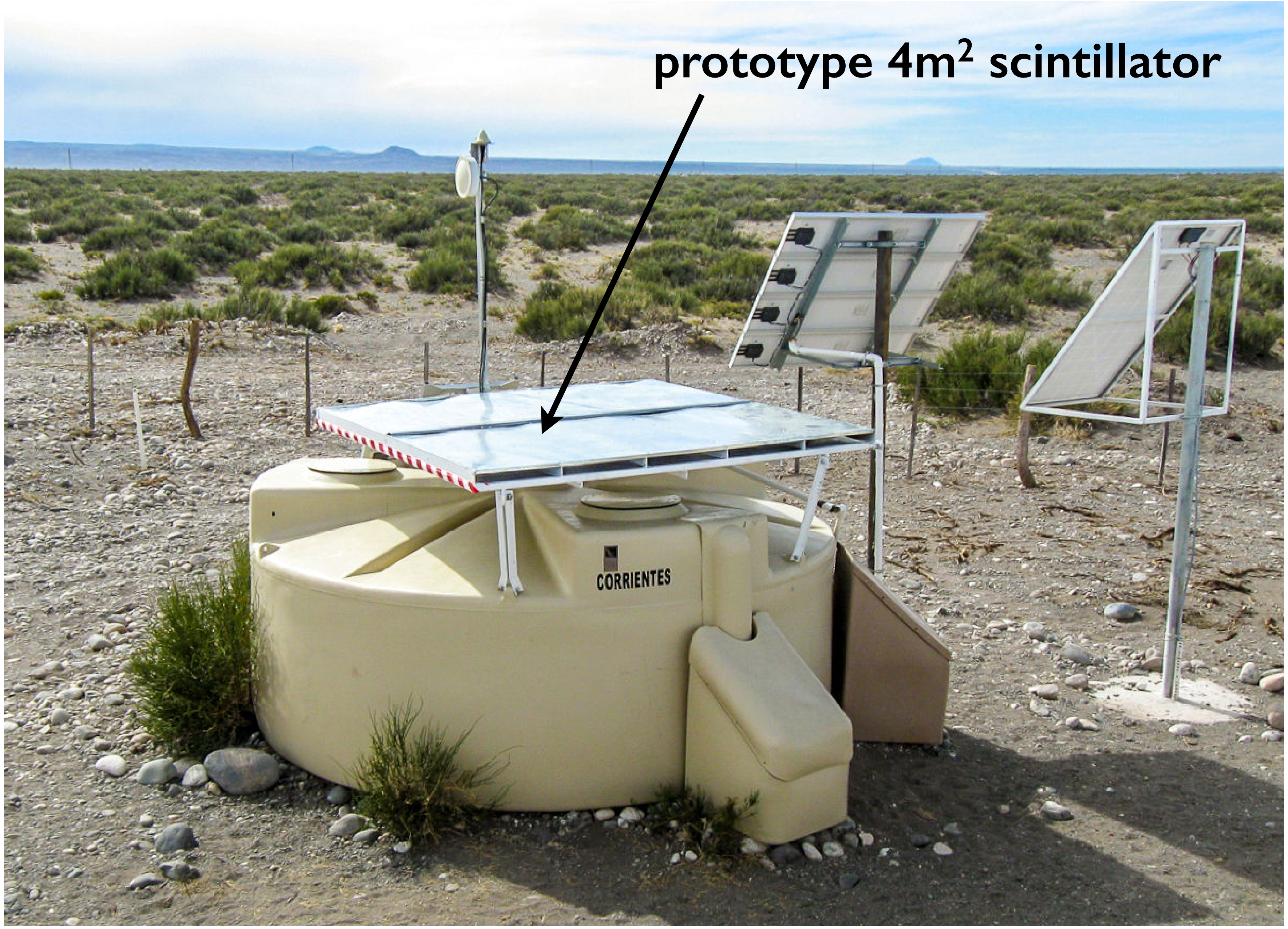
- particle physics beyond man-made colliders (e.g. cross sections)
- derivation of constraints on new physics phenomena (e.g. extra dimensions)

Proposed Auger upgrade for beyond 2015

1) Upgrade aging SD electronics for faster sampling and better event reconstruction

2) Install new detector on SDs for better muon-to-electromagnetic signal discrimination

- scintillator on top of WCD



Proposed Auger upgrade for beyond 2015

1) Upgrade aging SD electronics for faster sampling and better event reconstruction

2) Install new detector on SDs for better muon-to-electromagnetic signal discrimination
   - scintillator on top of WCD

- Upgrade case presented to an International Scientific Advisory Committee in March 2014 to evaluate its scientific merit
  ➡ **strongly supports the Auger upgrade science**

Operate until 2023

Ultra High Energy Cosmic Rays

What are they?

- Something more than mere p and Fe nuclei
- Intermediate species play a bigger role than expected
- Puzzling: lack of p and Fe at currently available highest energy

Where are they coming from?

- Around $E=5\times10^{18}$ eV (ankle): limit some models that explain ankle feature
- Suppression ($E>4\times10^{19}$ eV): need larger statistics

How do they **interact?**

- Measurement of X_{max} distribution actively helps to understand hadronic interactions at $E_{CM} \gtrsim 35$ TeV
- Manmade collider: LHC's 14 TeV data will help, information on forward region crucial

Summary

- Auger Observatory collected sufficient data to obtain distribution of X_{max};
- X_{max} distribution data analyzed by creating MC template;
- Surprising results:
  - incompatible with composition dominated by protons + iron nuclei;
  - intermediate (helium, nitrogen) nuclei required for acceptable fit qualities;
  - considerable presence of protons below ankle region;
  - general behavior of protons similar for all three hadronic interaction models;
  - able to constrain a hadronic interaction model in some cases;
- Observed trend may be due to deviations from the standard extrapolation in hadronic interaction models;
- Upgrade Auger detectors to understand the cause of flux suppression through better composition determination; will be proposed by the international collaboration.